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Altonen et al.

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(54) **INJECTION MOLDING MACHINES AND METHODS FOR ACCOUNTING FOR CHANGES IN MATERIAL PROPERTIES DURING INJECTION MOLDING RUNS**

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CPC B29C 2945/76076; B29C 2945/76257; B29C 2945/76381; B29C 2945/76933
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,642,404	A	2/1972	Nagawa
4,889,667	A	12/1989	Kojima
4,968,462	A	11/1990	Hara
5,419,858	A	5/1995	Hata et al.
5,578,256	A	11/1996	Austin
5,665,283	A	9/1997	Bader
5,945,046	A	8/1999	Hehl

(Continued)

OTHER PUBLICATIONS

International Search Report/Written Opinion for PCT/US2014/049108, mailed Nov. 17, 2014, 11 pages.

(Continued)

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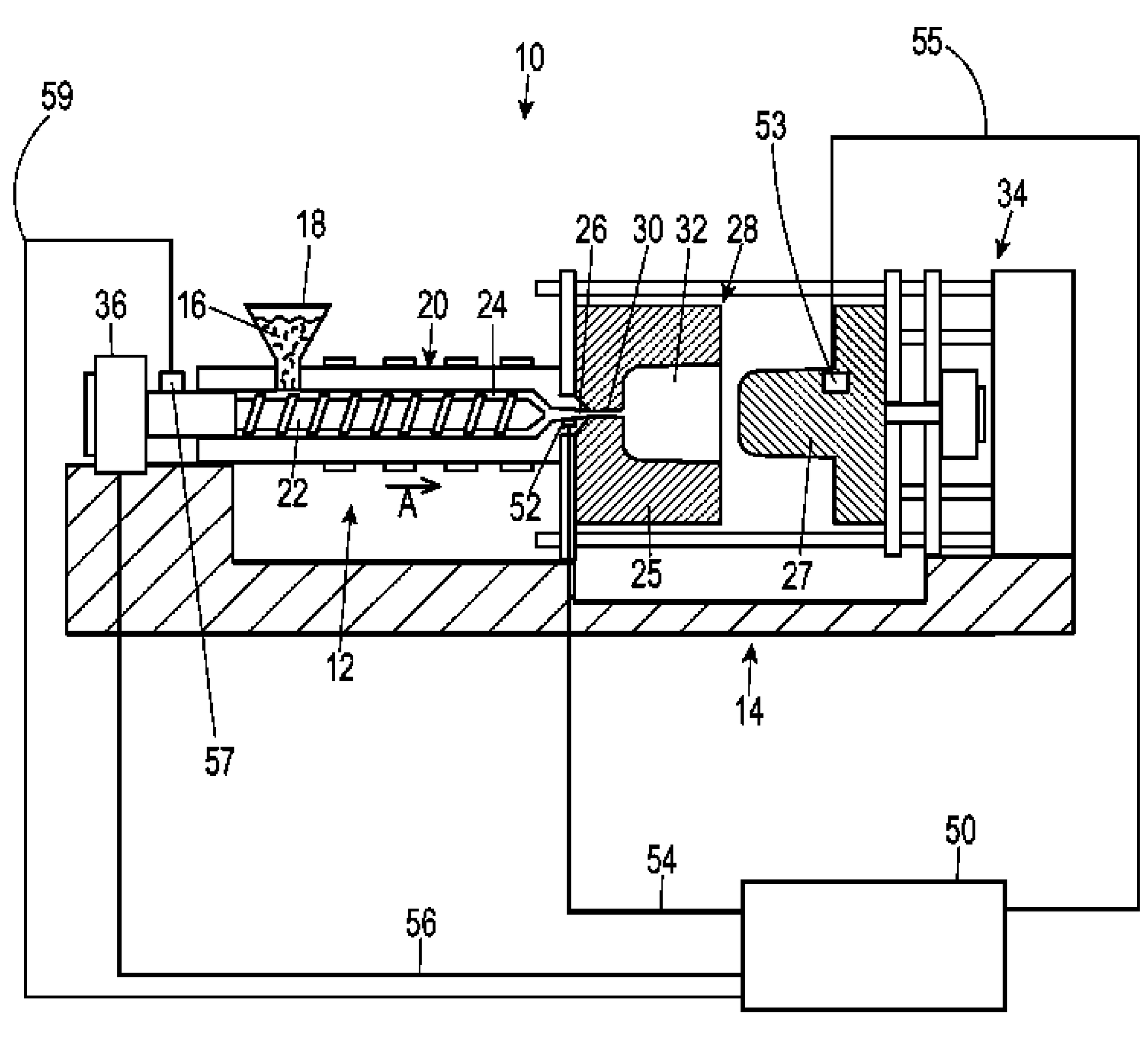
(57) **ABSTRACT**

A method and a machine account for changes in material properties of molten plastic material during an injection run. A change in a control signal is calculated by a controller during the injection molding run. If the change in the control signal indicates a change in material flowability, the controller alters a target injection pressure to ensure that molten plastic material completely fills and packs a mold cavity to prevent part flaws such as short shots or flashing.

20 Claims, 11 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

6,968,240	B2	11/2005	Frey
7,071,712	B2	7/2006	Frey
7,430,923	B2	10/2008	Bader
7,431,871	B2	10/2008	Frey
7,476,095	B2	1/2009	Bader
7,597,827	B2	10/2009	Frey
7,644,620	B2	1/2010	Bader
7,682,535	B2	3/2010	Frey
7,931,837	B2	4/2011	Bader
8,329,075	B2	12/2012	Bader
8,828,291	B2	9/2014	Altonen
8,920,703	B2	12/2014	Bader
2002/0022066	A1	2/2002	Matsubayashi
2004/0084794	A1	5/2004	Frey
2006/0022363	A1	2/2006	Konno
2007/0296102	A1	12/2007	Hofmann
2012/0292823	A1	11/2012	Altonen
2012/0294963	A1	11/2012	Altonen
2012/0295049	A1	11/2012	Altonen
2012/0295050	A1	11/2012	Altonen
2012/0328724	A1	12/2012	Altonen
2012/0329948	A1	12/2012	Altonen
2013/0069280	A1	3/2013	Altonen
2013/0221575	A1	8/2013	Altonen
2013/0334721	A1	12/2013	Bader

OTHER PUBLICATIONS

Patent Examination Report No. 1, Australian Patent Application No. 2014296127, dated Aug. 4, 2016.
U.S. Appl. No. 14/176,505, filed Feb. 10, 2014, Altonen.
U.S. Appl. No. 14/448,648, filed Jul. 31, 2014, Altonen.
U.S. Appl. No. 14/448,682, filed Jul. 31, 2014, Altonen.
U.S. Appl. No. 14/577,310, filed Dec. 19, 2014, Newman.
U.S. Appl. No. 62/045,373, filed Sep. 3, 2014, Altonen.
U.S. Appl. No. 62/053,499, filed Sep. 22, 2014, Altonen.
U.S. Appl. No. 62/084,778, filed Dec. 8, 2014, Ward.
U.S. Appl. No. 62/084,787, filed Dec. 8, 2014, Ward.
Facts Inc., Process Control Systems brochure, 1528-00, 2 pp. (May 1, 2012).
Toshiba Machine, All Electric Injection Molding Machine EC-SX Medium and Large-size Series, 4 pp. (Oct. 2, 2012).
Toshiba Machine, B-1 Five New Technologies of the Injection Molding Machine Series EC-SX, 6 pp. (May 9, 2012).
Toshiba Machine, INJECTVISOR-S50, 3 pp. (Oct. 3, 2012).
Toshiba Machine, INJECTVISOR-V30, 3 pp. (Oct. 3, 2012).

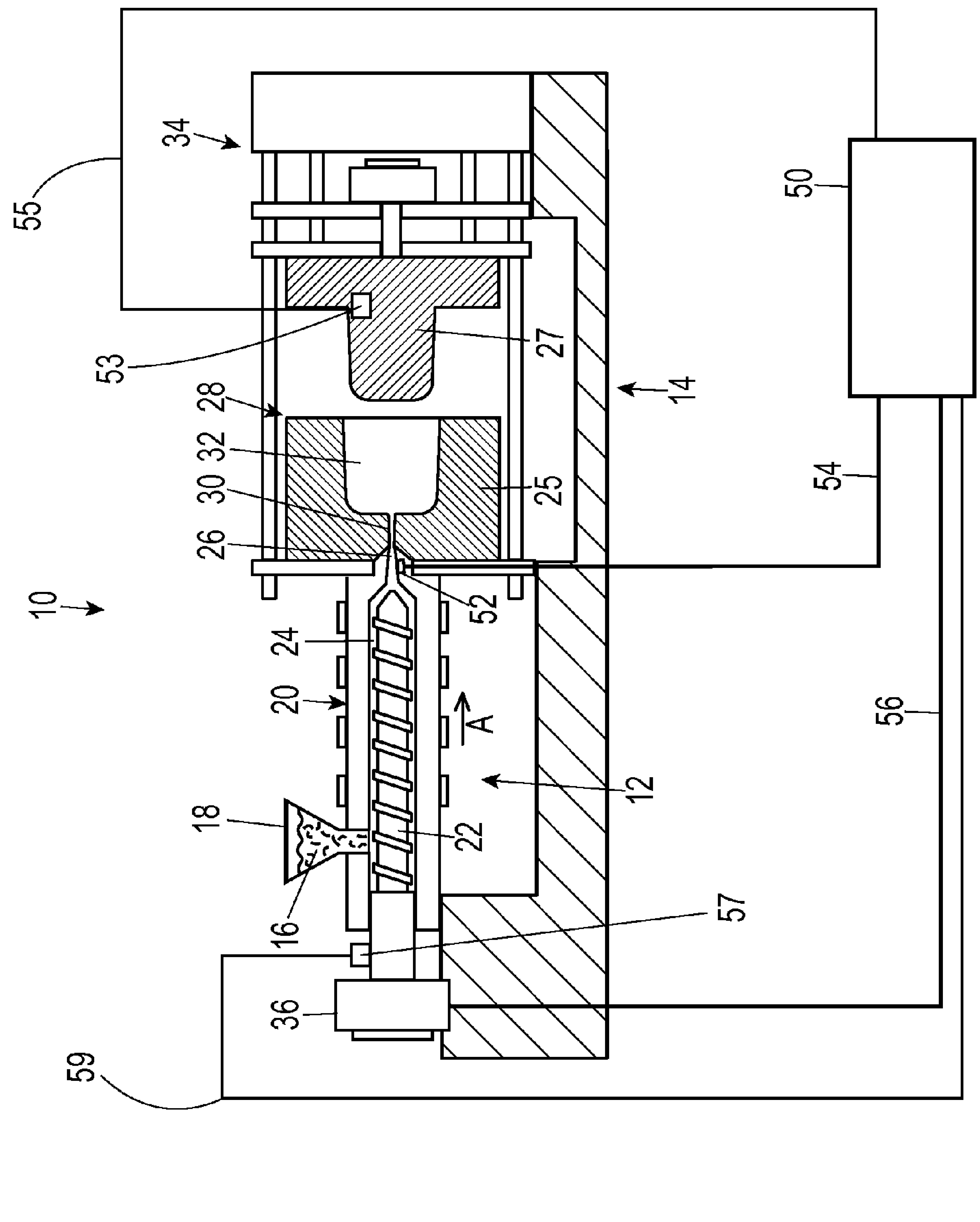


Fig. 1

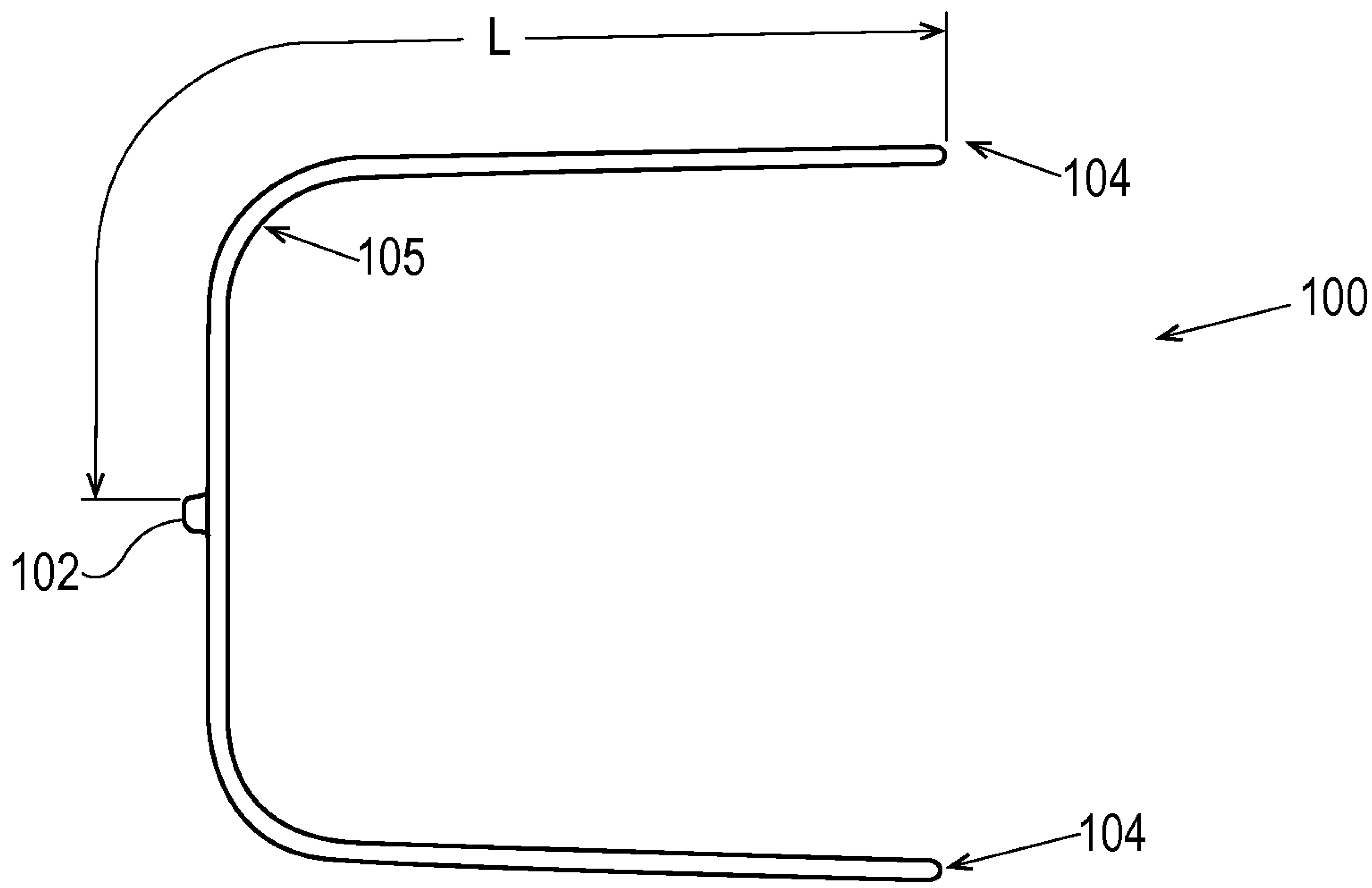


Fig. 2

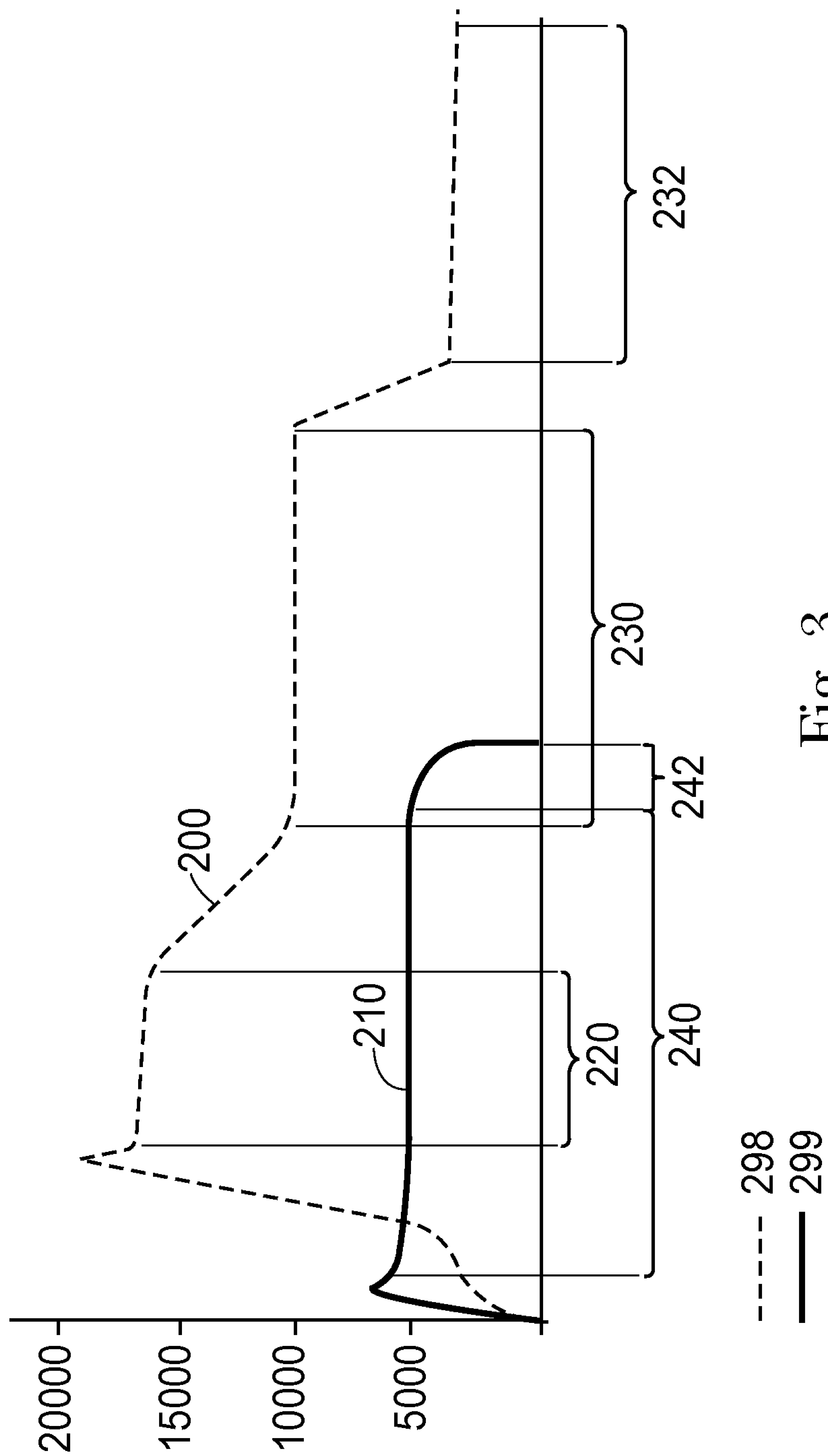


Fig. 3

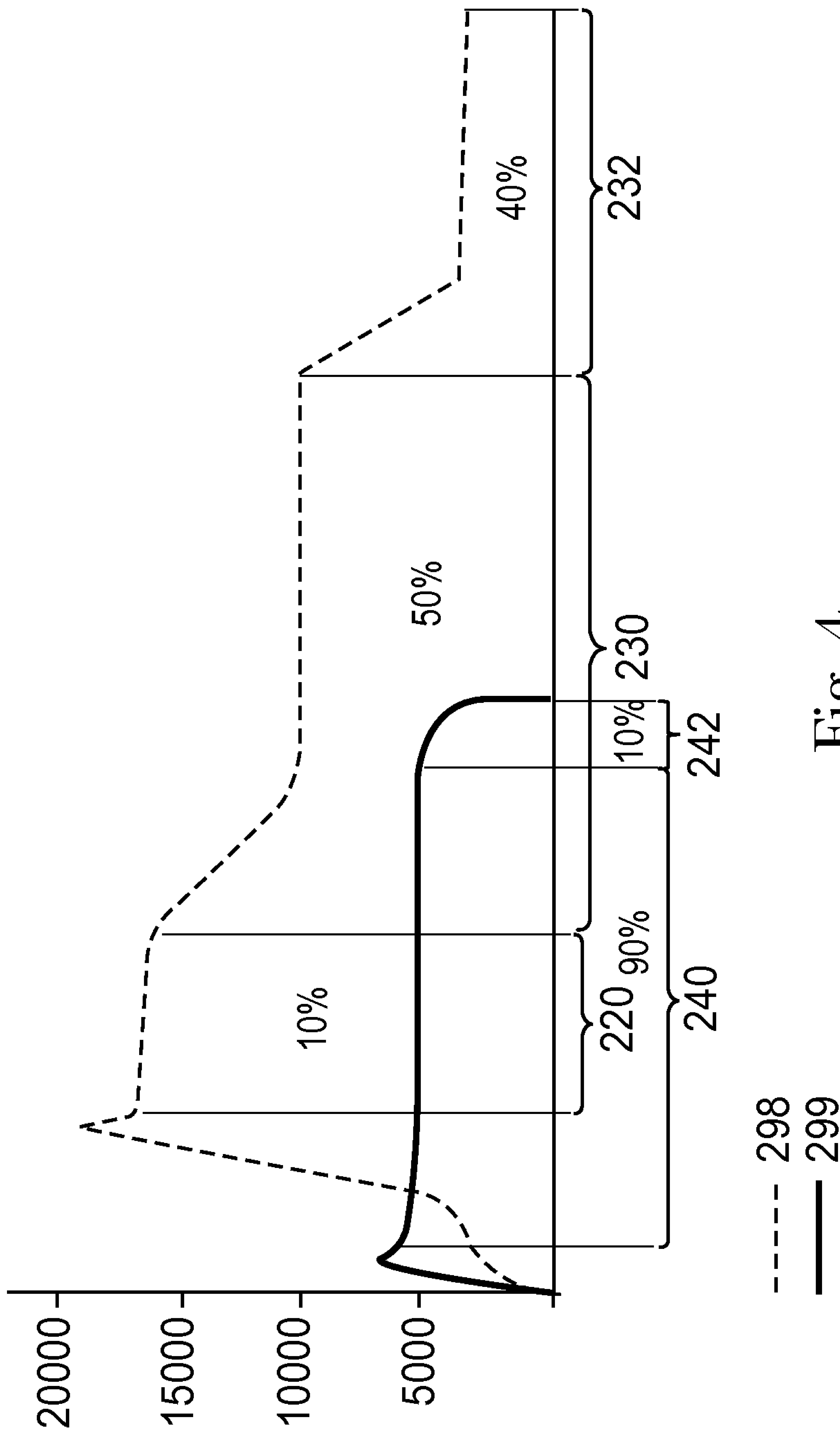

20000
15000
10000
5000
10%
50%
40%
90%
10%
220
230
232
240
242
298
299

Fig. 4

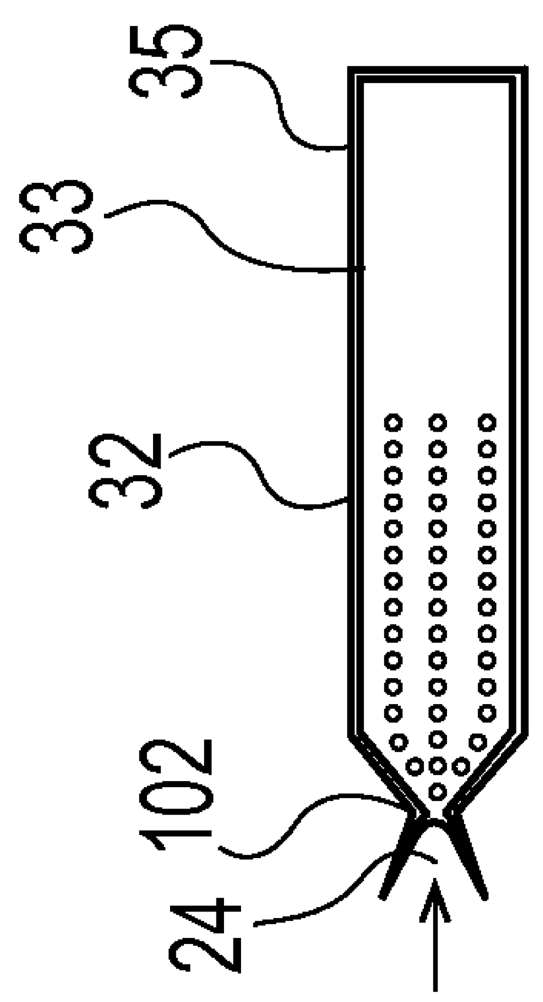


Fig. 5B

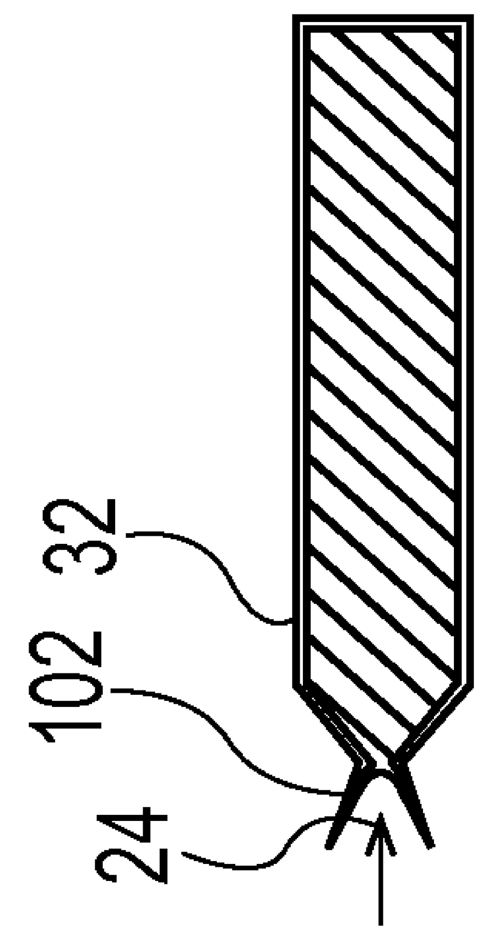


Fig. 5D

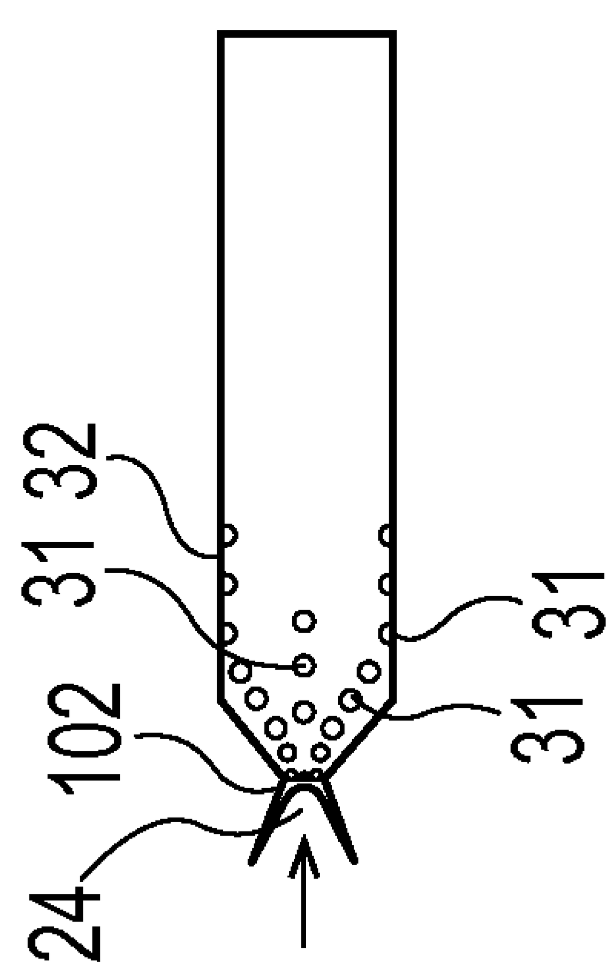


Fig. 5A

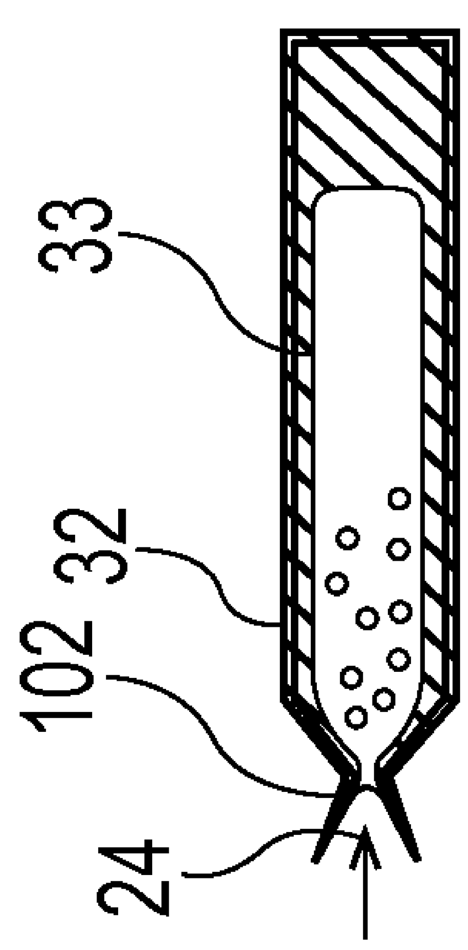


Fig. 5C

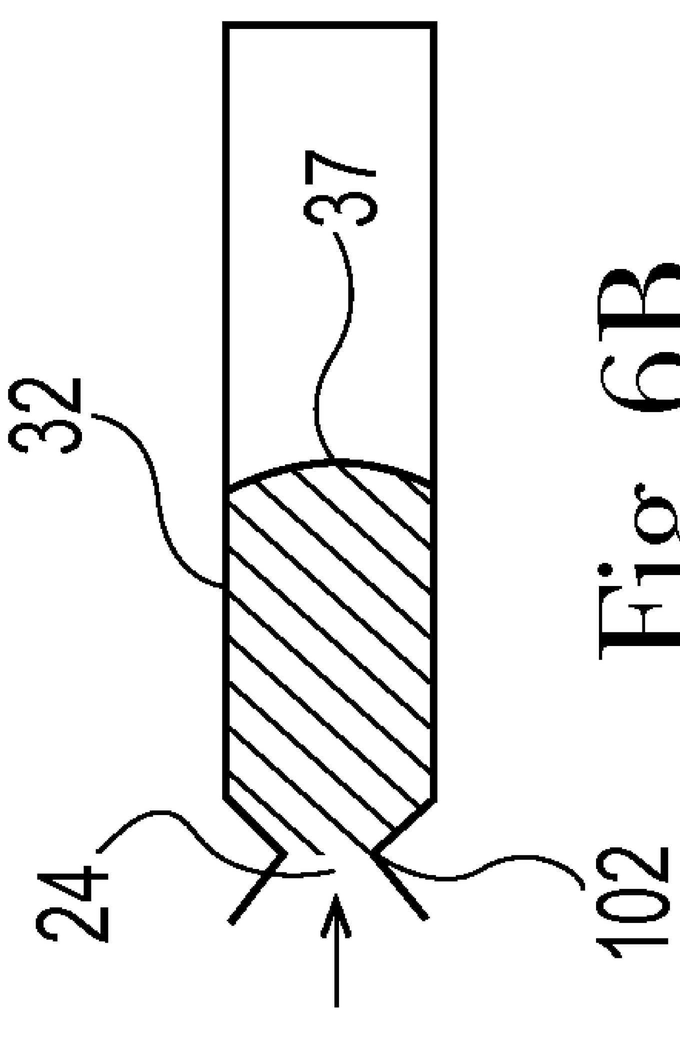


Fig. 6B

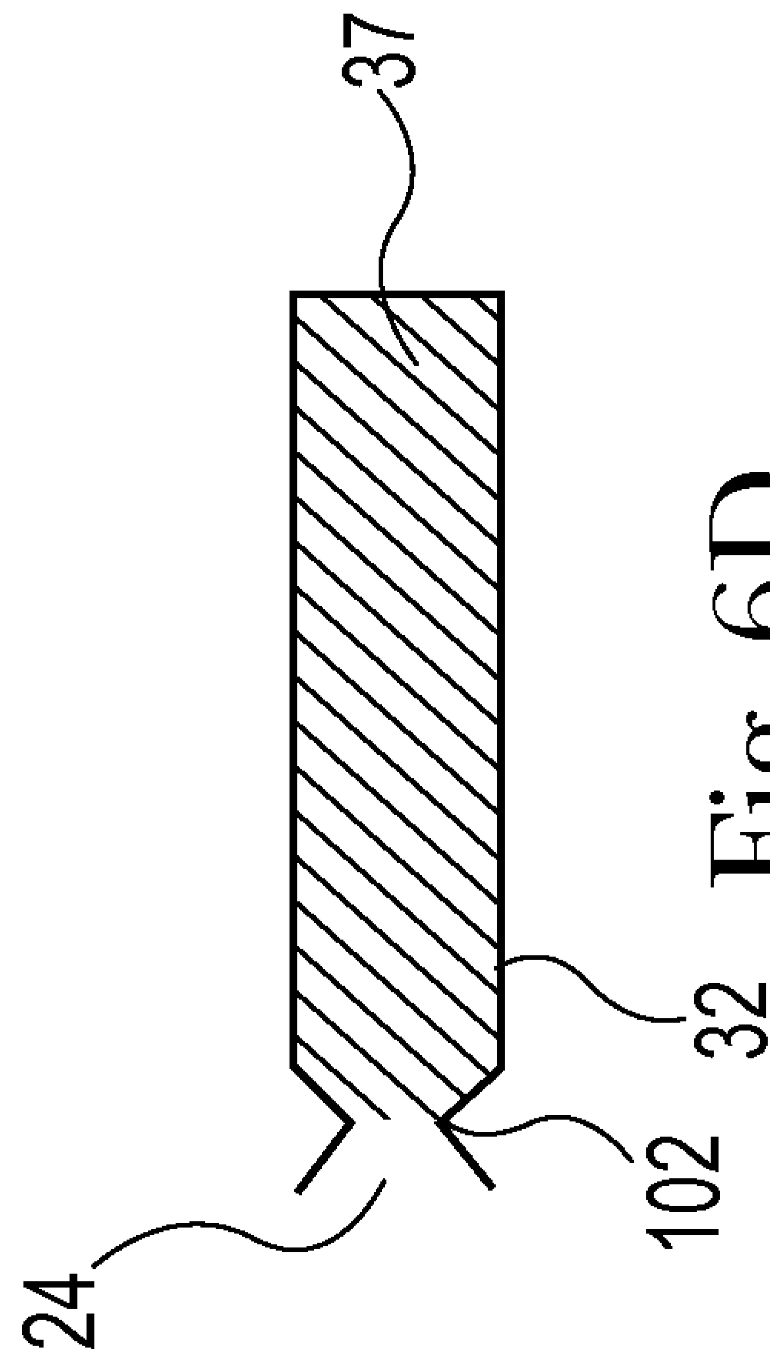


Fig. 6D

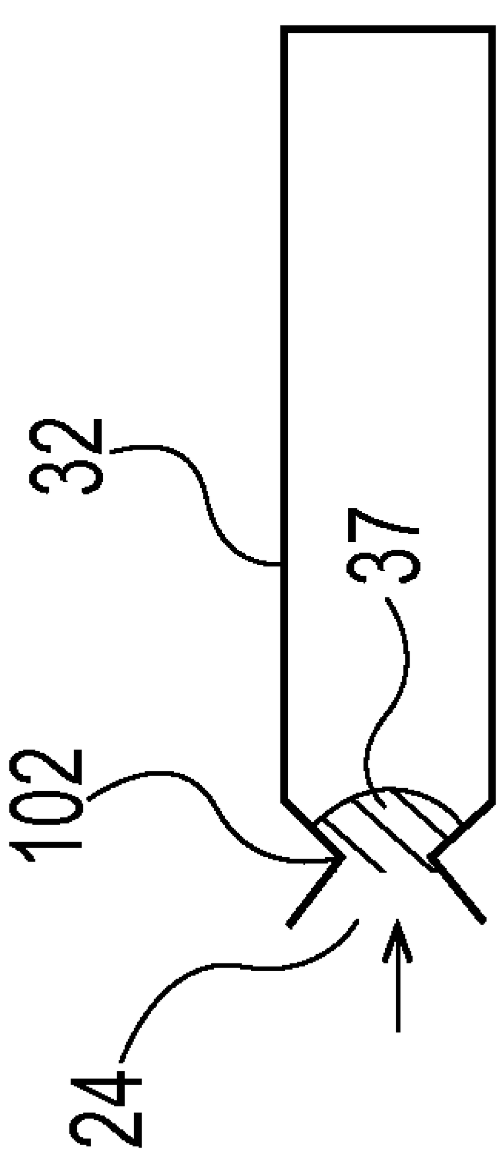


Fig. 6A

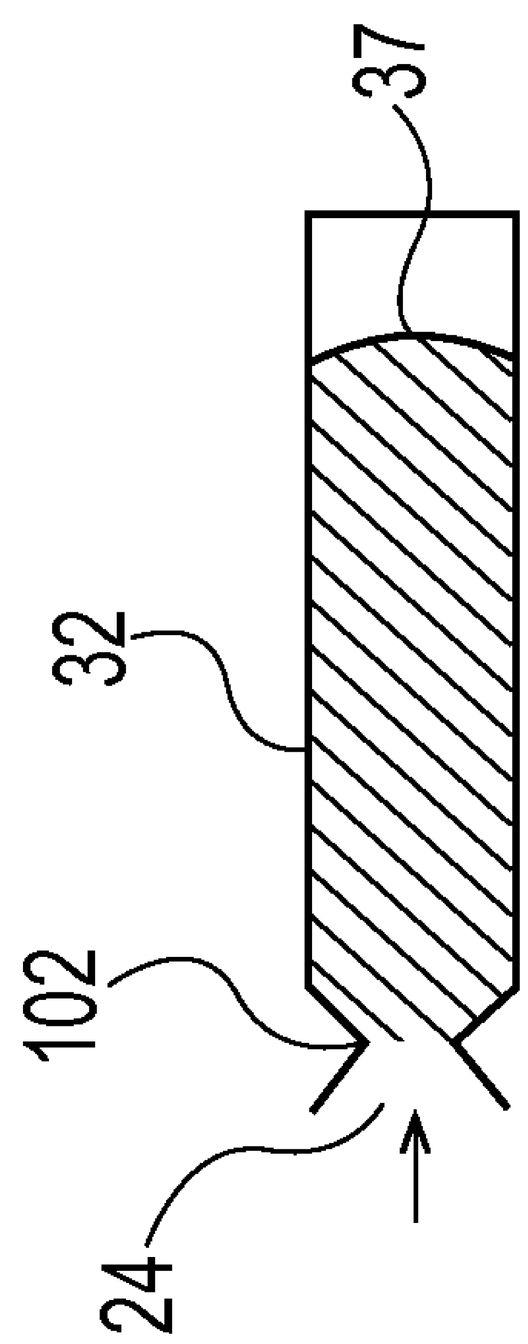


Fig. 6C

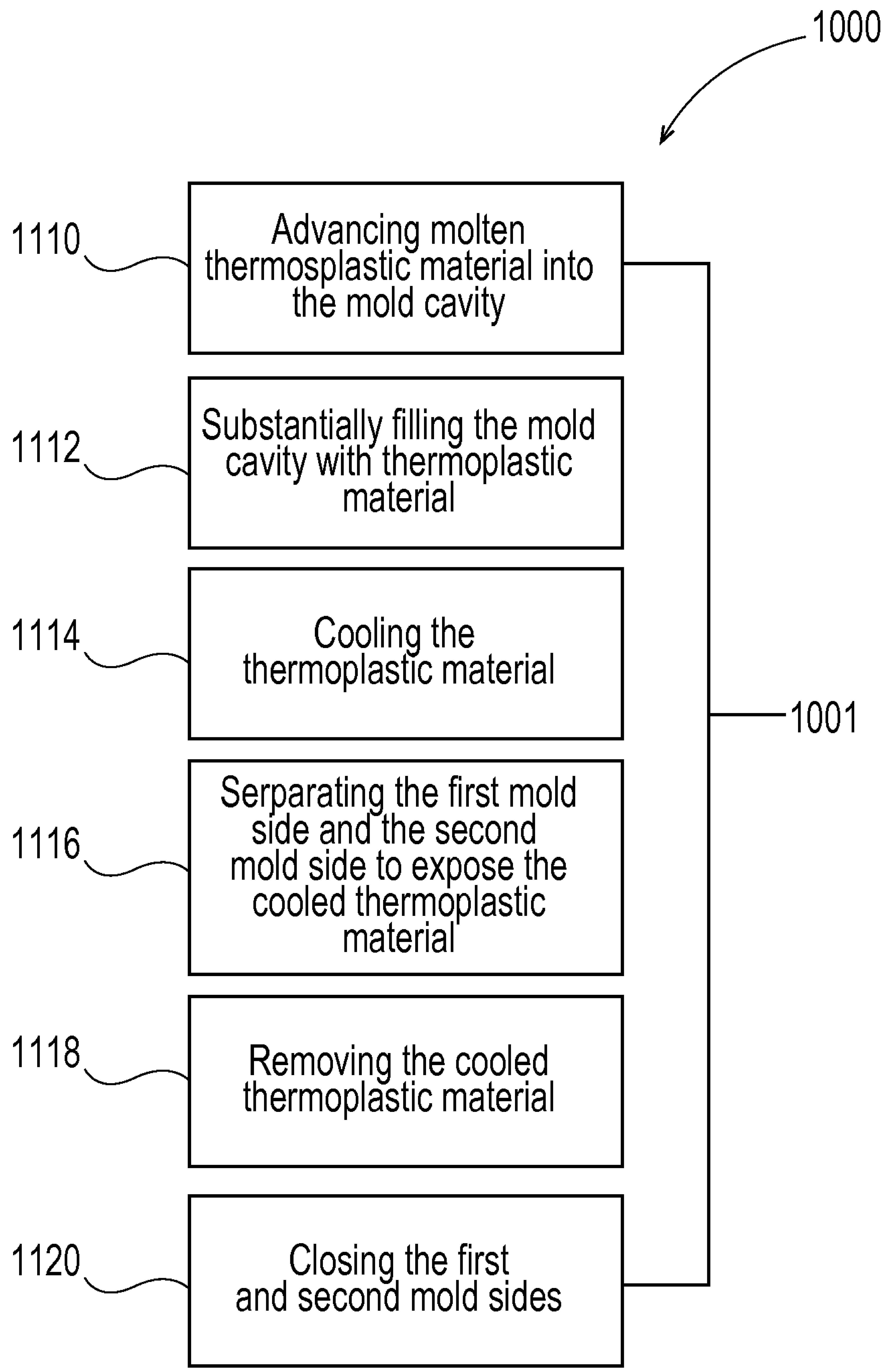

1000
1110
Advancing molten thermosplastic material into the mold cavity
1112
Substantially filling the mold cavity with thermoplastic material
1114
Cooling the thermoplastic material
1116
Serparating the first mold side and the second mold side to expose the cooled thermoplastic material
1118
Removing the cooled thermoplastic material
1120
Closing the first and second mold sides
1001

Fig. 7

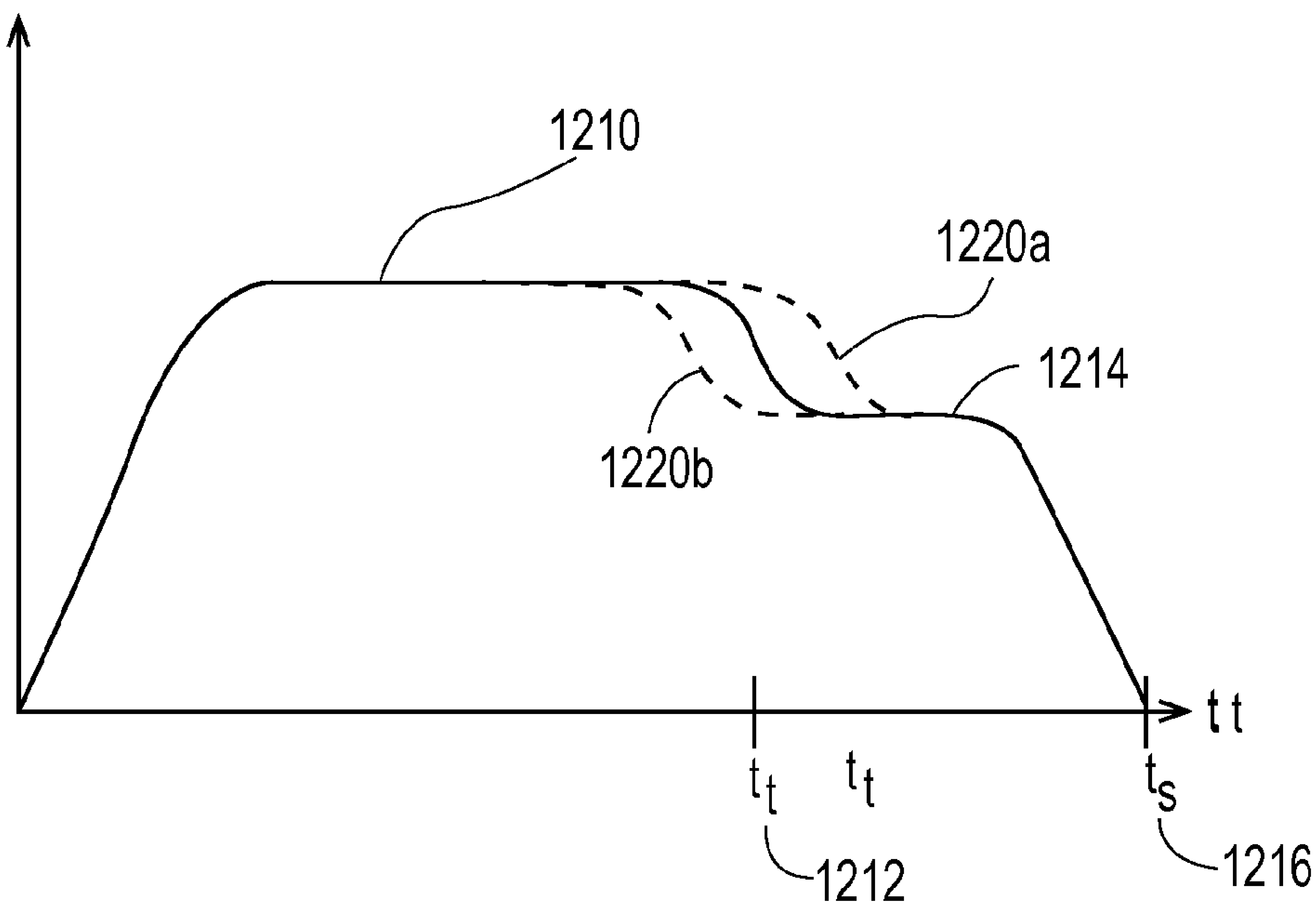


Fig. 8

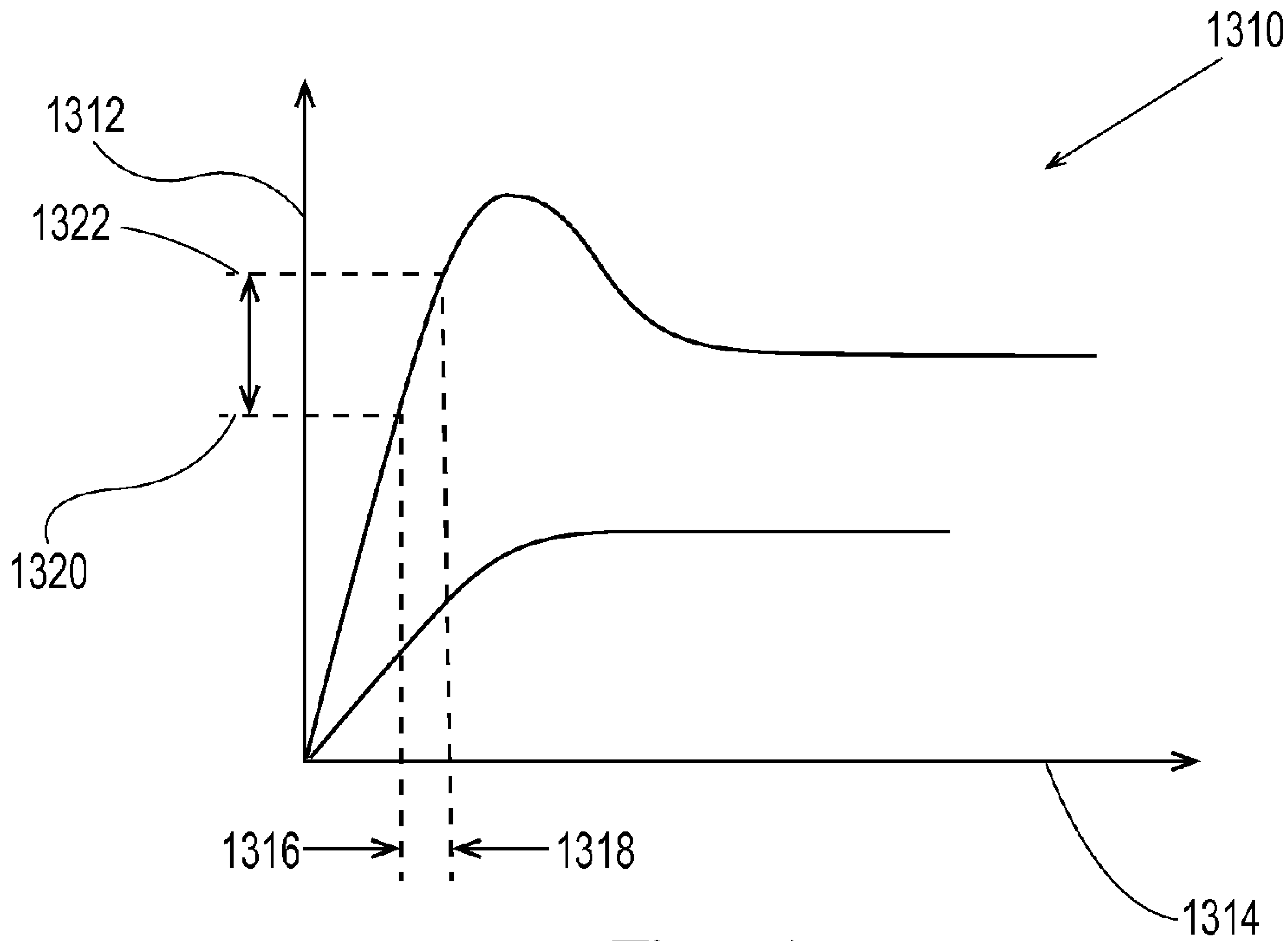

1310
1312
1322
1320
1316
1318
1314

Fig. 9A

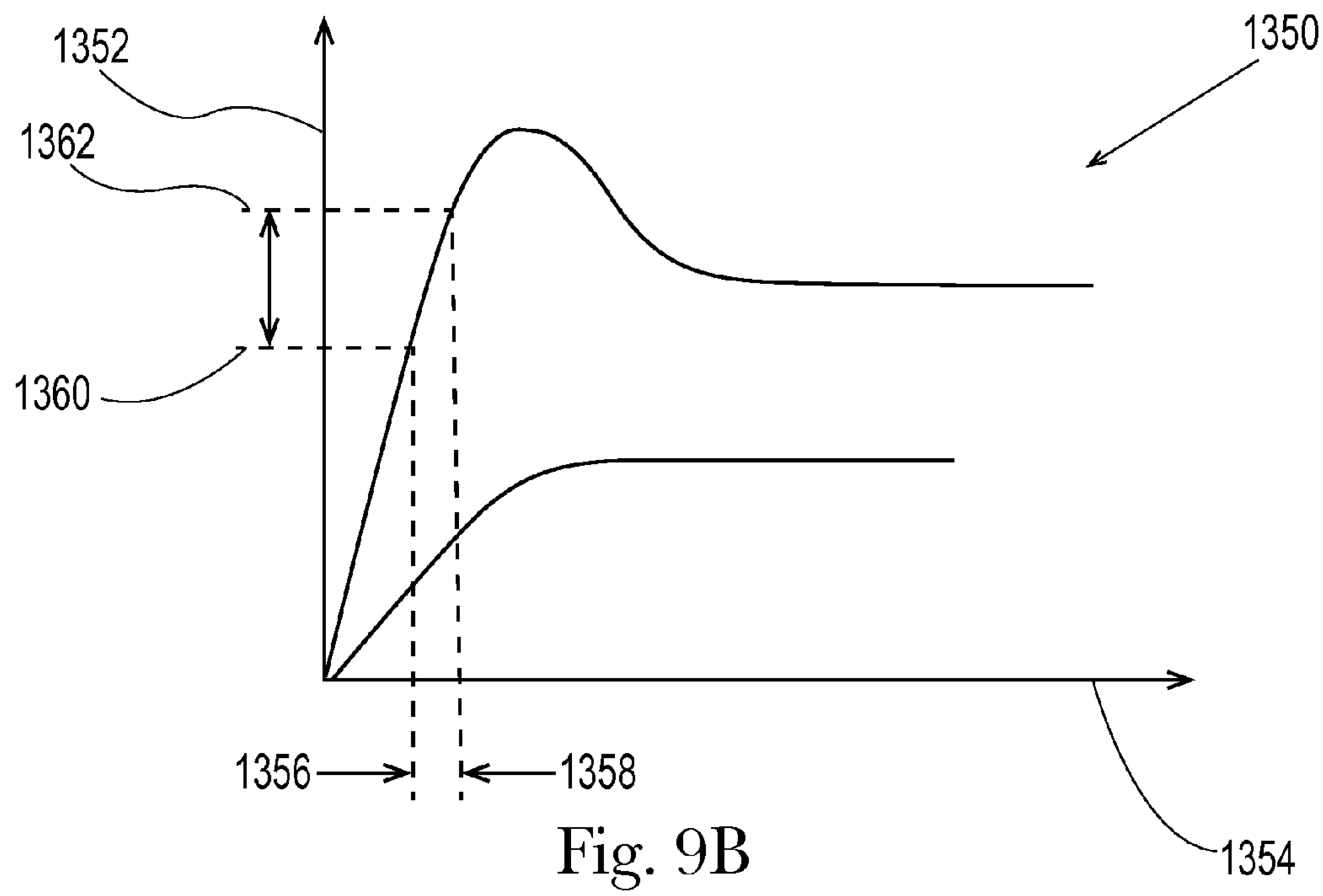

1350
1352
1362
1360
1356
1358
1354

Fig. 9B

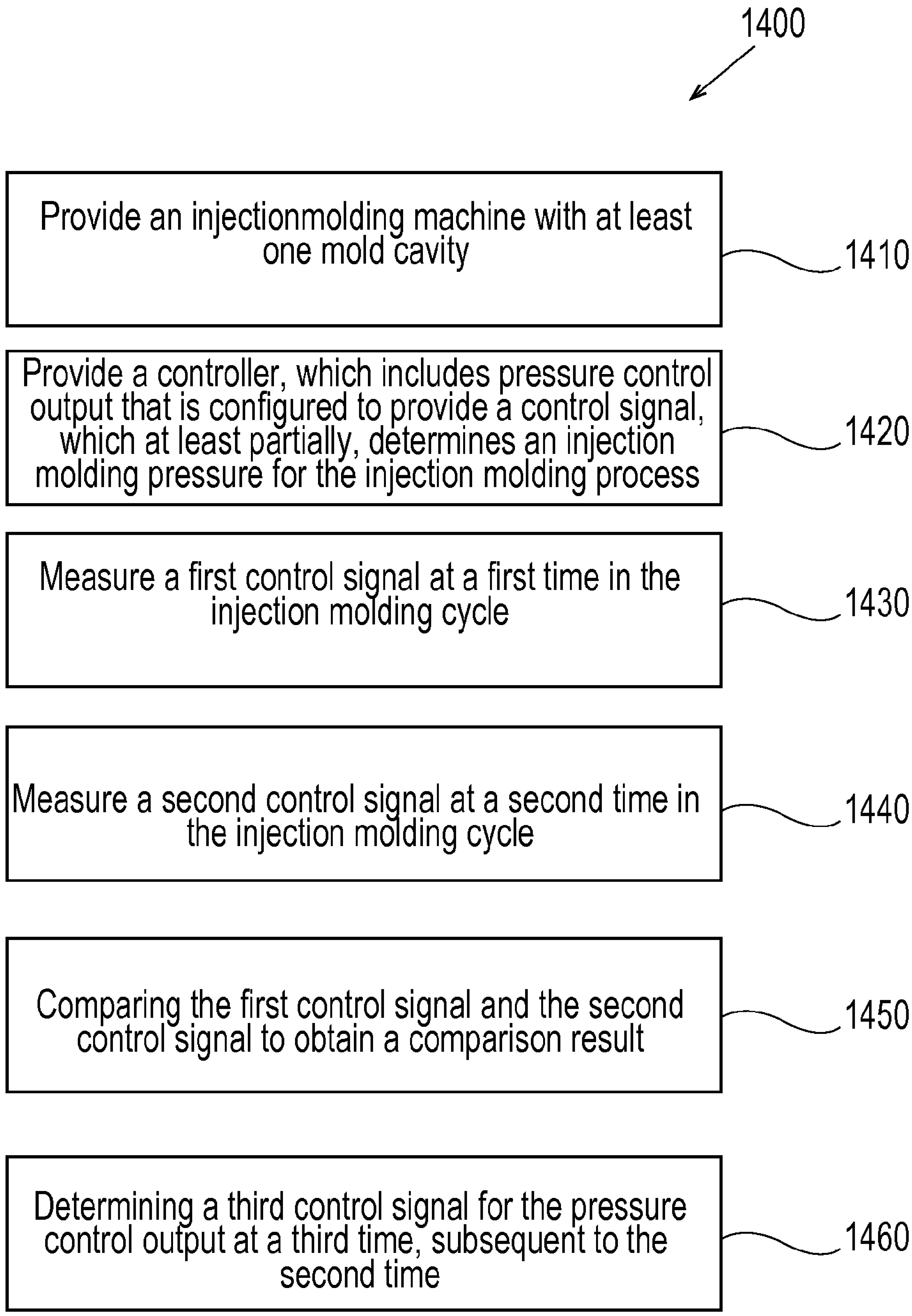

1400
Provide an injectionmolding machine with at least one mold cavity
1410
Provide a controller, which includes pressure control output that is configured to provide a control signal, which at least partially, determines an injection molding pressure for the injection molding process
1420
Measure a first control signal at a first time in the injection molding cycle
1430
Measure a second control signal at a second time in the injection molding cycle
1440
Comparing the first control signal and the second control signal to obtain a comparison result
1450
Determining a third control signal for the pressure control output at a third time, subsequent to the second time
1460

Fig. 10

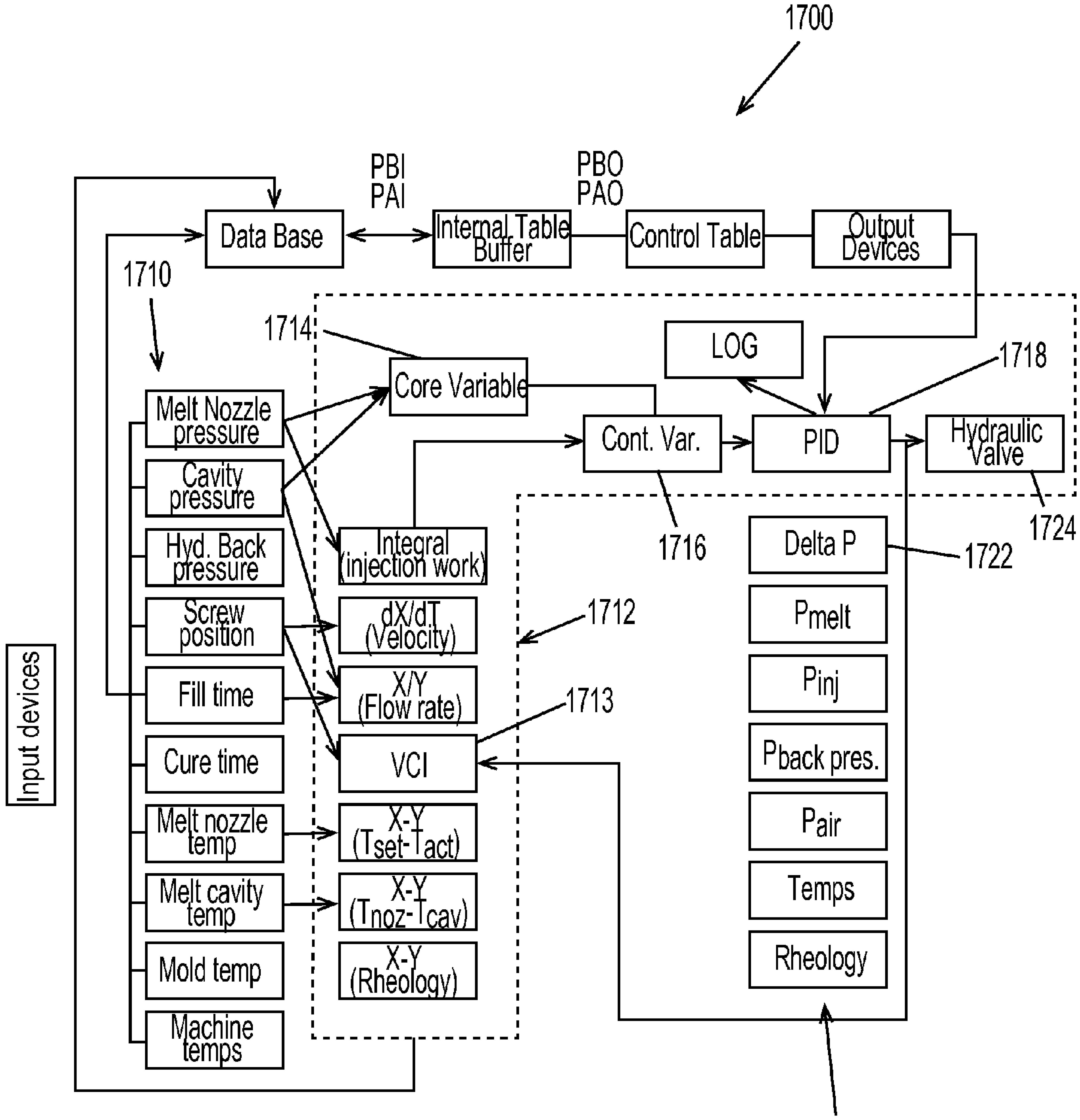

1700
PBI
PAI
PBO
PAO
Data Base
Internal Table Buffer
Control Table
Output Devices
1710
1714
Core Variable
LOG
1718
Cont. Var.
PID
Hydraulic Valve
Melt Nozzle pressure
Cavity pressure
Hyd. Back pressure
Screw position
Fill time
Cure time
Melt nozzle temp
Melt cavity temp
Mold temp
Machine temps
Input devices
Integral (injection work)
dX/dT (Velocity)
X/Y (Flow rate)
VCI
X-Y (Tset-Tact)
X-Y (Tnoz-Tcav)
X-Y (Rheology)
1716
1724
1722
1712
1713
Delta P
Pmelt
Pinj
Pback pres.
Pair
Temps
Rheology
1720

Fig. 11

INJECTION MOLDING MACHINES AND METHODS FOR ACCOUNTING FOR CHANGES IN MATERIAL PROPERTIES DURING INJECTION MOLDING RUNS

TECHNICAL FIELD OF THE INVENTION

The present invention relates to injection molding machines and methods of producing injection molded parts and, more particularly, to injection molding machines that adjust operating parameters of the injection molding machine during an injection molding run to account for changes in material properties of the injection material and methods of accounting for changes in injection molding material properties during an injection molding run.

BACKGROUND OF THE INVENTION

Injection molding is a technology commonly used for high-volume manufacturing of parts made of meltable material, most commonly of parts made of thermoplastic polymers. During a repetitive injection molding process, a plastic resin, most often in the form of small beads or pellets, is introduced to an injection molding machine that melts the resin beads under heat, pressure, and shear. The now molten resin is forcefully injected into a mold cavity having a particular cavity shape. The injected plastic is held under pressure in the mold cavity, cooled, and then removed as a solidified part having a shape that essentially duplicates the cavity shape of the mold. The mold itself may have a single cavity or multiple cavities. Each cavity may be connected to a flow channel by a gate, which directs the flow of the molten resin into the cavity. A molded part may have one or more gates. It is common for large parts to have two, three, or more gates to reduce the flow distance the polymer must travel to fill the molded part. The one or multiple gates per cavity may be located anywhere on the part geometry, and possess any cross-section shape such as being essentially circular or be shaped with an aspect ratio of 1.1 or greater. Thus, a typical injection molding procedure comprises four basic operations: (1) heating the plastic in the injection molding machine to allow the plastic to flow under pressure; (2) injecting the melted plastic into a mold cavity or cavities defined between two mold halves that have been closed; (3) allowing the plastic to cool and harden in the cavity or cavities while under pressure; and (4) opening the mold halves and ejecting the part from the mold.

During the injection molding process, the molten plastic resin is injected into the mold cavity and the plastic resin is forcibly injected into the cavity by the injection molding machine until the plastic resin reaches the location in the cavity furthest from the gate. Thereafter, the plastic resin fills the cavity from the end back towards the gate. The resulting length and wall thickness of the part is a result of the shape of the mold cavity.

In some cases, it may be desirous to reduce the wall thickness of injected molded parts to reduce the plastic content, and thus cost, of the final part. Reducing wall thickness using a conventional high variable pressure injection molding process can be an expensive and a non-trivial task. In fact, conventional injection molding machines (e.g. machines injecting molten plastic resin between about 8,000 psi and about 20,000 psi) have a practical limit as to how thin walls of a part may be molded. Generally speaking, conventional injection molding machines cannot mold parts having a thinwall ratio (as defined by an L/T ratio set forth below) of greater than about 200. Furthermore, molding thinwall parts with thinwall ratios of more than 100 requires pressures at the high end of current capability and thus, presses that are capable of handling these high pressures.

When filling a thinwall part, the current industry practice is to fill the mold cavity at the highest possible rate the molding machine can achieve. This approach ensures that the mold cavity is filled before the polymer solidifies or "freezes off" in the mold, and provides the lowest possible cycle time since the polymer is exposed to the cooled mold cavity as quickly as possible. This approach has two drawbacks. The first is that to achieve very high filling velocities requires very high power loads, and this requires very expensive molding equipment. Further, most electric presses are unable to provide sufficient power to achieve these high filling rates, or require very complicated and expensive drive systems that substantially increase the cost of the molding equipment making them impractical economically.

The second drawback is that the high filling rates require very high pressures. These high pressures result in the need for very high clamping forces to hold the mold closed during filling, and these high clamping forces result in very expensive molding equipment. The high pressures also require injection mold cores that are made from very high strength materials, typically hardened tool steels. These high strength molds are also very expensive, and can be impractical economically for many molded components. Even with these substantial drawbacks, the need for thinwall injection molded components remains high, since these components use less polymer material to form the molded part, thereby resulting in material savings that more than offset the higher equipment costs. Further, some molded components require very thin design elements to perform properly, such as design elements that need to flex, or design elements that must mate with very small features of other design elements.

As a liquid plastic resin is introduced into an injection mold in a conventional injection molding process the material adjacent to the walls of the cavity, immediately begins to "freeze," or solidify, or cure, or in the case of crystalline polymers the plastic resin begins to crystallize, because the liquid plastic resin cools to a temperature below the material's no flow temperature and portions of the liquid plastic become stationary. This frozen material adjacent to the walls of the mold narrows the flow path that the thermoplastic travels as it progresses to the end of the mold cavity. The thickness of the frozen material layer adjacent to the walls of the mold increases as the filling of the mold cavity progresses, this causes a progressive reduction in the cross sectional area the polymer must flow through to continue to fill the mold cavity. As material freezes, it also shrinks, pulling away from the mold cavity walls, which reduces effective cooling of the material by the mold cavity walls. As a result, conventional injection molding machines fill the mold cavity with plastic very quickly and then maintain a packing pressure to force the material outward against the sides of the mold cavity to enhance cooling and to maintain the correct shape of the molded part. Conventional injection molding machines typically have cycle times made up of about 10% injection time, about 50% packing time, and about 40% cooling time.

As plastic freezes in the mold cavity, conventional injection molding machines increase injection pressure (to maintain a substantially constant volumetric flow rate due to the smaller cross-sectional flow area). Increasing the pressure, however, has both cost and performance downsides. As the pressure required to mold the component increases, the molding equipment must be strong enough to withstand the additional pressure, which generally equates to being more expensive. A manufacturer may have to purchase new equipment to accommodate these increased pressures. Thus, a decrease in the wall thickness of a given part can result in significant capital expenses to accomplish the manufacturing via conventional injection molding techniques.

In an effort to avoid some of the drawbacks mentioned above, many conventional injection molding operations use shear-thinning plastic material to improve flow characteristics of the plastic material into the mold cavity. As the shear-thinning plastic material is injected into the mold cavity, shear forces generated between the plastic material and the mold cavity walls tend to reduce viscosity of the plastic material, thereby allowing the plastic material to flow more freely and easily into the mold cavity. As a result, it is possible to fill thinwall parts fast enough to avoid the material completely freezing off before the mold is completely filled.

Reduction in viscosity is directly related to the magnitude of shear forces generated between the plastic material and the feed system, and between the plastic material and the mold cavity wall. Thus, manufacturers of these shear-thinning materials and operators of injection molding systems have been driving injection molding pressures higher in an effort to increase shear, thus reducing viscosity. Typically, high output injection molding systems (e.g., class 101 and class 30 systems) inject the plastic material in to the mold cavity at melt pressures of typically 15,000 psi or more. Manufacturers of shear-thinning plastic material teach injection molding operators to inject the plastic material into the mold cavities above a minimum melt pressure. For example, polypropylene resin is typically processed at pressures greater than 6,000 psi (the recommended range from the polypropylene resin manufacturers, is typically from greater than 6,000 psi to about 15,000 psi). Press manufacturers and processing engineers typically recommend processing shear thinning polymers at the top end of the range, or significantly higher, to achieve maximum potential shear thinning, which is typically greater than 15,000 psi, to extract maximum thinning and better flow properties from the plastic material. Shear thinning thermoplastic polymers generally are processed in the range of over 6,000 psi to about 30,000 psi. Even with the use of shear thinning plastics, a practical limit exists for high variable pressure injection molding of thin walled parts. This limit is currently in the range of thinwall parts having a thinwall ratio of 200 or more. Moreover, even parts having a thinwall ratio of between 100 and 200 may become cost prohibitive as these parts generally require injection pressures between about 15,000 psi and about 20,000 psi.

High production injection molding machines (i.e., class 101 and class 30 molding machines) that produce thinwalled consumer products exclusively use molds having a majority of the mold made from high hardness materials. High production injection molding machines typically experience 500,000 cycles per year or more. Industrial quality production molds must be designed to withstand at least 500,000 cycles per year, preferably more than 1,000,000 cycles per year, more preferably more than 5,000,000 cycles per year, and even more preferably more than 10,000,000 cycles per year. These machines have multi cavity molds and complex cooling systems to increase production rates. The high hardness materials are more capable of withstanding the repeated high pressure clamping operations than lower hardness materials. However, high hardness materials, such as most tool steels, have relatively low thermal conductivities, generally less than 20 BTU/HR FT ° F., which leads to long

cooling times as heat is transferred through from the molten plastic material through the high hardness material.

Even with the ever increasing injection pressure ranges of existing high variable pressure injection molding machines, a practical limit remains of about 200 (L/T ratio) for molding thinwalled parts in conventional high (e.g., 20,000 psi) variable pressure injection molding machines and thinwall parts having a thinwall ratio of between about 100 and about 200 may be cost prohibitive for many manufacturers.

Changes in molding conditions can significantly affect properties of the molten plastic material. More specifically, changes in environmental conditions (such as changes in temperature) can raise or lower the viscosity of the molten plastic material. When viscosity of the molten plastic material changes, quality of the molded part may be impacted. For example, if the viscosity of the molten plastic material increases the molded part may experience a short shot, or a shortage of molten plastic material. On the other hand, if the viscosity of the molten plastic material decreases the molded part may experience flashing as the thinner molten plastic material is pressed into the seam of the mold cavity. Furthermore, recycled plastic material that is mixed with virgin material may change a melt flow index (MFI) of the combined plastic material. Conventional injection molding machines do not adjust operating parameters to account for these changes in material properties. As a result, conventional injection molding machines can produce lower quality parts, which must be removed during quality-control inspections, thereby leading to operational inefficiencies.

BRIEF DESCRIPTION OF THE DRAWINGS

The embodiments set forth in the drawings are illustrative and exemplary in nature and not intended to limit the subject matter defined by the claims. The following detailed description of the illustrative embodiments can be understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. **1** illustrates a schematic view of an injection molding machine constructed according to the disclosure;

FIG. **2** illustrates one embodiment of a thin-walled part formed in the injection molding machine of FIG. **1**;

FIG. **3** is a cavity pressure vs. time graph for the injection molding machine of FIG. **1** superimposed over a cavity pressure vs. time graph for a conventional injection molding machine;

FIG. **4** is another cavity pressure vs. time graph for the injection molding machine of FIG. **1** superimposed over a cavity pressure vs. time graph for a conventional injection molding machine, the graphs illustrating the percentage of fill time devoted to certain fill steps;

FIGS. **5**A-**5**D are side cross-sectional views of a portion of a thinwall mold cavity in various stages of fill by a conventional injection molding machine;

FIGS. **6**A-**6**D are side cross-sectional views of a portion of a thinwall mold cavity in various stages of fill by the injection molding machine of FIG. **1**;

FIG. **7** is a schematic illustration of an injection molding cycle that may be carried out on the injection molding machine of FIG. **1**;

FIG. **8** is a pressure vs. time graph for an injection molding machine that illustrates the effect of variations in viscosity of the molten plastic material;

FIG. **9**A is a graph that illustrates changes in control signal voltage over time during an injection molding cycle;

FIG. 9B is a graph that illustrates changes in control signal voltage over a distance traveled for a melt moving machine component;

FIG. 10 is a logic diagram that illustrates an injection molding process that accounts for viscosity changes in the molten plastic material; and

FIG. 11 is a schematic diagram of a control system that may be used to implement the logic diagram of FIG. 10.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention generally relate to systems, machines, products, and methods of producing products by injection molding and more specifically to systems, products, and methods of producing products by low substantially constant pressure injection molding. However, the devices and methods for accounting for viscosity changes in the molten plastic material described herein are not limited to low substantially constant pressure injection molding machines and processes. Rather, the disclosed devices and methods for accounting for viscosity changes in the molten plastic material may be incorporated into virtually any injection molding machine or process, including, but not limited to, high pressure processes, low pressure processes, variable pressure processes, and constant or substantially constant pressure processes.

The term "low pressure" as used herein with respect to melt pressure of a thermoplastic material, means melt pressures in a vicinity of a nozzle of an injection molding machine of 15,000 psi and lower.

The term "substantially constant pressure" as used herein with respect to a melt pressure of a thermoplastic material, means that deviations from a baseline melt pressure do not produce meaningful changes in physical properties of the thermoplastic material. For example, "substantially constant pressure' includes, but is not limited to, pressure variations for which viscosity of the melted thermoplastic material do not meaningfully change. The term "substantially constant" in this respect includes deviations of approximately 30% from a baseline melt pressure. For example, the term "a substantially constant pressure of approximately 4600 psi" includes pressure fluctuations within the range of about 6000 psi (30% above 4600 psi) to about 3200 psi (30% below 4600 psi). A melt pressure is considered substantially constant as long as the melt pressure fluctuates no more than 30% from the recited pressure.

The term "melt holder", as used herein, refers to the portion of an injection molding machine that contains molten plastic in fluid communication with the machine nozzle. The melt holder is heated, such that a polymer may be prepared and held at a desired temperature. The melt holder is connected to a power source, for example a hydraulic cylinder or electric servo motor, that is in communication with a central control unit, and can be controlled to advance a diaphragm to force molten plastic through the machine nozzle. The molten material then flows through the runner system in to the mold cavity. The melt holder may be cylindrical in cross section, or have alternative cross sections that will permit a diaphragm to force polymer under pressures that can range from as low as 100 psi to pressures 40,000 psi or higher through the machine nozzle. The diaphragm may optionally be integrally connected to a reciprocating screw with flights designed to plasticize polymer material prior to injection.

The term "high L/T ratio" generally refers to L/T ratios of 100 or greater, and more specifically to L/T ratios of 200 or greater, but less than 1000. Calculation of the L/T ratio is defined below. The term "peak flow rate" generally refers to the maximum volumetric flow rate, as measured at the machine nozzle.

The term "peak injection rate" generally refers to the maximum linear speed the injection ram travels in the process of forcing polymer in to the feed system. The ram can be a reciprocating screw such as in the case of a single stage injection system, or a hydraulic ram such as in the case of a two stage injection system.

The term "ram rate" generally refers to the linear speed the injection ram travels in the process of forcing polymer into the feed system.

The term "flow rate" generally refers to the volumetric flow rate of polymer as measured at the machine nozzle. This flow rate can be calculated based on the ram rate and ram cross sectional area, or measured with a suitable sensor located in the machine nozzle.

The term "cavity percent fill" generally refers to the percentage of the cavity that is filled on a volumetric basis. For example, if a cavity is 95% filled, then the total volume of the mold cavity that is filled is 95% of the total volumetric capacity of the mold cavity.

The term "melt temperature" generally refers to the temperature of the polymer that is maintained in the melt holder, and in the material feed system when a hot runner system is used, which keeps the polymer in a molten state. The melt temperature varies by material, however, a desired melt temperature is generally understood to fall within the ranges recommended by the material manufacturer.

The term "gate size" generally refers to the cross sectional area of a gate, which is formed by the intersection of the runner and the mold cavity. For hot runner systems, the gate can be of an open design where there is no positive shut off of the flow of material at the gate, or a closed design where a valve pin is used to mechanically shut off the flow of material through the gate in to the mold cavity (commonly referred to as a valve gate). The gate size refers to the cross sectional area, for example a 1 mm gate diameter refers to a cross sectional area of the gate that is equivalent to the cross sectional area of a gate having a 1 mm diameter at the point the gate meets the mold cavity. The cross section of the gate may be of any desired shape.

The term "effective gate area" generally refers to a cross sectional area of a gate corresponding to an intersection of the mold cavity and a material flow channel of a feed system (e.g., a runner) feeding thermoplastic to the mold cavity. The gate could be heated or not heated. The gate could be round, or any cross sectional shape, suited to achieve the desired thermoplastic flow into the mold cavity. The term "intensification ratio" generally refers to the mechanical advantage the injection power source has on the injection ram forcing the molten polymer through the machine nozzle. For hydraulic power sources, it is common that the hydraulic piston will have a 10:1 mechanical advantage over the injection ram. However, the mechanical advantage can range from ratios much lower, such as 2:1, to much higher mechanical advantage ratio such as 50:1.

The term "peak power" generally refers to the maximum power generated when filling a mold cavity. The peak power may occur at any point in the filling cycle. The peak power is determined by the product of the plastic pressure as measured at the machine nozzle multiplied by the flow rate as measured at the machine nozzle. Power is calculated by the formula $P=p*Q$ where p is pressure and Q is volumetric flow rate.

The term "volumetric flow rate" generally refers to the flow rate as measured at the machine nozzle. This flow rate can be calculated based on the ram rate and ram cross sectional area, or measured with a suitable sensor located in the machine nozzle.

The terms "filled" and "full," when used with respect to a mold cavity including thermoplastic material, are interchangeable and both terms mean that thermoplastic material has stopped flowing into the mold cavity.

The term "shot size" generally refers to the volume of polymer to be injected from the melt holder to completely fill the mold cavity or cavities. The Shot Size volume is determined based on the temperature and pressure of the polymer in the melt holder just prior to injection. In other words, the shot size is a total volume of molten plastic material that is injected in a stroke of an injection molding ram at a given temperature and pressure. Shot size may include injecting molten plastic material into one or more injection cavities through one or more gates. The shot of molten plastic material may also be prepared and injected by one or more melt holders.

The term "hesitation" generally refers to the point at which the velocity of the flow front is minimized sufficiently to allow a portion of the polymer to drop below its no flow temperature and begin to freeze off.

The term "electric motor" or "electric press," when used herein includes both electric servo motors and electric linear motors.

The term "Peak Power Flow Factor" refers to a normalized measure of peak power required by an injection molding system during a single injection molding cycle and the Peak Power Flow Factor may be used to directly compare power requirements of different injection molding systems. The Peak Power Flow Factor is calculated by first determining the Peak Power, which corresponds to the maximum product of molding pressure multiplied by flow rate during the filling cycle (as defined herein), and then determining the Shot Size for the mold cavities to be filled. The Peak Power Flow Factor is then calculated by dividing the Peak Power by the Shot Size.

The term "low constant pressure injection molding machine" is defined as a class 101 or a class 30 injection molding machine that uses a substantially constant injection pressure that is less than 15,000 psi. Alternatively, the term "low constant pressure injection molding machine" may be defined as an injection molding machine that uses a substantially constant injection pressure that is less than 15,000 psi and that is capable of performing more than 1 million cycles, preferably more than 1.25 million cycles, more preferably more than 2 million cycles, more preferably more than 5 million cycles, and even more preferably more than 10 million cycles before the mold core (which is made up of first and second mold parts that define a mold cavity therebetween) reaches the end of its useful life. Characteristics of "low constant pressure injection molding machines" include mold cavities having an L/T ratio of greater than 100 (and preferably greater than 200), multiple mold cavities (preferably 4 mold cavities, more preferably 16 mold cavities, more preferably 32 mold cavities, more preferably 64 mold cavities, more preferably 128 mold cavities and more preferably 256 mold cavities, or any number of mold cavities between 4 and 512), a heated runner, and a guided ejection mechanism.

The term "useful life" is defined as the expected life of a mold part before failure or scheduled replacement. When used in conjunction with a mold part or a mold core (or any part of the mold that defines the mold cavity), the term "useful life" means the time a mold part or mold core is expected to be in service before quality problems develop in the molded part, before problems develop with the integrity of the mold part (e.g., galling, deformation of parting line, deformation or excessive wear of shut-off surfaces), or before mechanical failure (e.g., fatigue failure or fatigue cracks) occurs in the mold part. Typically, the mold part has reached the end of its "useful life" when the contact surfaces that define the mold cavity must be discarded or replaced. The mold parts may require repair or refurbishment from time to time over the "useful life" of a mold part and this repair or refurbishment does not require the complete replacement of the mold part to achieve acceptable molded part quality and molding efficiency. Furthermore, it is possible for damage to occur to a mold part that is unrelated to the normal operation of the mold part, such as a part not being properly removed from the mold and the mold being force ably closed on the non-ejected part, or an operator using the wrong tool to remove a molded part and damaging a mold component. For this reason, spare mold parts are sometimes used to replace these damaged components prior to them reaching the end of their useful life. Replacing mold parts because of damage does not change the expected useful life.

The term "guided ejection mechanism" is defined as a dynamic part that actuates to physically eject a molded part from the mold cavity.

The term "coating" is defined as a layer of material less than 0.13 mm (0.005 in) in thickness, that is disposed on a surface of a mold part defining the mold cavity, that has a primary function other than defining a shape of the mold cavity (e.g., a function of protecting the material defining the mold cavity, or a function of reducing friction between a molded part and a mold cavity wall to enhance removal of the molded part from the mold cavity).

The term "average thermal conductivity" is defined as the thermal conductivity of any materials that make up the mold cavity or the mold side or mold part. Materials that make up coatings, stack plates, support plates, and gates or runners, whether integral with the mold cavity or separate from the mold cavity, are not included in the average thermal conductivity. Average thermal conductivity is calculated on a volume weighted basis.

The term "effective cooling surface" is defined as a surface through which heat is removed from a mold part. One example of an effective cooling surface is a surface that defines a channel for cooling fluid from an active cooling system. Another example of an effective cooling surface is an outer surface of a mold part through which heat dissipates to the atmosphere. A mold part may have more than one effective cooling surface and thus may have a unique average thermal conductivity between the mold cavity surface and each effective cooling surface.

The term "nominal wall thickness" is defined as the theoretical thickness of a mold cavity if the mold cavity were made to have a uniform thickness. The nominal wall thickness may be approximated by the average wall thickness. The nominal wall thickness may be calculated by integrating length and width of the mold cavity that is filled by an individual gate.

The term "average hardness" is defined as the Rockwell hardness for any material or combination of materials in a desired volume. When more than one material is present, the average hardness is based on a volume weighted percentage of each material. Average hardness calculations include hardnesses for materials that make up any portion of the mold cavity. Average hardness calculations do not include materials that make up coatings, stack plates, gates or runners, whether integral with a mold cavity or not, and support plates. Generally, average hardness refers to the volume weighted hardness of material in the mold cooling region.

The term "mold cooling region" is defined as a volume of material that lies between the mold cavity surface and an effective cooling surface.

The term "cycle time" or "injection molding cycle" is defined as a single iteration of an injection molding process that is required to fully form an injection molded part. Cycle time, or injection molding cycle, includes the steps of advancing molten thermoplastic material into a mold cavity, substantially filling the mold cavity with thermoplastic material, cooling the thermoplastic material, separating first and second mold sides to expose the cooled thermoplastic material, removing the thermoplastic material, and closing the first and second mold sides.

The term "injection molding run," as used herein, includes a series of sequential injection molding cycles that are performed on a common injection molding machine.

The term "flowability," as used herein, includes the flow resistance of a molten plastic material as it flows through an injection molding system and accounts for all influences on the relative viscosity of the molten plastic material, including, but not limited to, composition of the molten plastic material, temperature, shear, mold design, and part design.

The term "flow factor" is defined as a ratio of a control signal for a proportional valve to an incremental time period. This ratio may be expressed in voltage/time, for example, in millivolts/microsecond. This ratio may be determined for any type of injection press (e.g., a hydraulic press or an electric press) and may be calculated by the formula: $FF=(CS1-CS2)/T$, where CS1 and CS2 are control signals measured over an incremental time period.

The term "viscosity change index" is defined as a ratio of a control signal for a proportional valve over a given distance of travel for a melt moving machine component, such as an injection screw, in an injection molding machine. This ratio may be expressed in voltage/distance, for example, in millivolts/micron. This ratio may be determined for any type of injection press (e.g., a hydraulic press or an electric press) and may be calculated by the formula: $VCI=(CS1-CS2)/S$, where CS1 is a first control signal, CS2 is a second control signal, and S is a distance of travel for a melt moving machine component.

The term "proportional valve" is defined as a valve that moves in proportion to an electronic control signal. For example, if an electronic control signal increases by 10%, the proportional valve will open to allow 10% more material to flow through the valve.

Low constant pressure injection molding machines may also be high productivity injection molding machines (e.g., a class 101 or a class 30 injection molding machine, or an "ultra high productivity molding machine"), such as the high productivity injection molding machine disclosed in U.S. patent application Ser. No. 13/601,514, filed Aug. 31, 2012, which is hereby incorporated by reference herein, that may be used to produce thinwalled consumer products, such as toothbrush handles and razor handles. Thin walled parts are generally defined as having a high L/T ratio of 100 or more.

Referring to the figures in detail, FIG. **1** illustrates an exemplary low constant pressure injection molding apparatus **10** that generally includes an injection system **12** and a clamping system **14**. A thermoplastic material may be introduced to the injection system **12** in the form of thermoplastic pellets **16**. The thermoplastic pellets **16** may be placed into a hopper **18**, which feeds the thermoplastic pellets **16** into a heated barrel **20** of the injection system **12**. The thermoplastic pellets **16**, after being fed into the heated barrel **20**, may be driven to the end of the heated barrel **20** by a reciprocating screw **22**. The heating of the heated barrel **20** and the compression of the thermoplastic pellets **16** by the reciprocating screw **22** causes the thermoplastic pellets **16** to melt, forming a molten thermoplastic material **24**. The molten thermoplastic material is typically processed at a temperature of about 130° C. to about 410° C.

The reciprocating screw **22** forces the molten thermoplastic material **24**, toward a nozzle **26** to form a shot of thermoplastic material, which will be injected into a mold cavity **32** of a mold **28** via one or more gates **30**, preferably three or less gates, that direct the flow of the molten thermoplastic material **24** to the mold cavity **32**. In other embodiments the nozzle **26** may be separated from one or more gates **30** by a feed system (not shown). The mold cavity **32** is formed between first and second mold sides **25**, **27** of the mold **28** and the first and second mold sides **25**, **27** are held together under pressure by a press or clamping unit **34**. The press or clamping unit **34** applies a clamping force during the molding process that is greater than the force exerted by the injection pressure acting to separate the two mold halves **25**, **27**, thereby holding the first and second mold sides **25**, **27** together while the molten thermoplastic material **24** is injected into the mold cavity **32**. To support these clamping forces, the clamping system **14** may include a mold frame and a mold base.

Once the shot of molten thermoplastic material **24** is injected into the mold cavity **32**, the reciprocating screw **22** stops traveling forward. The molten thermoplastic material **24** takes the form of the mold cavity **32** and the molten thermoplastic material **24** cools inside the mold **28** until the thermoplastic material **24** solidifies. Once the thermoplastic material **24** has solidified, the press **34** releases the first and second mold sides **25**, **27**, the first and second mold sides **25**, **27** are separated from one another, and the finished part may be ejected from the mold **28**. The mold **28** may include a plurality of mold cavities **32** to increase overall production rates. The shapes of the cavities of the plurality of mold cavities may be identical, similar or different from each other. (The latter may be considered a family of mold cavities).

A controller **50** is communicatively connected with a nozzle sensor **52**, located in the vicinity of the nozzle **26**, an flow front sensor **53** located within the mold cavity **32** or proximate the mold cavity **32**, a linear transducer **57** located proximate the reciprocating screw **22**, and a screw control **36**. The controller **50** may include a microprocessor, a memory, and one or more communication links. The flow front sensor **53** may provide an indication of the location of a flow front of the molten plastic material flowing through the mold cavity **32**. While the flow front sensor **53** is illustrated near an end of the mold cavity **32** (e.g., the location in the mold cavity that is last to fill with molten plastic material) in FIG. **1**, the flow front sensor **53** may be located at any point in the mold cavity between a gate and the location of the mold cavity **32** that is last to fill with molten thermoplastic material. If the flow front sensor **53** is not located near the end of the mold cavity **32**, a time correction factor may be applied to approximate when the flow front of the molten plastic material will reach the end of the mold cavity **32**. It may be desirable to locate the flow front sensor **53** within 30% of an end of the mold cavity **32**, preferably within 20% of the end of the mold cavity **32**, and more preferably within 10% of the end of the mold cavity.

The linear transducer **57** may measure an amount of linear movement of the reciprocating screw **22**. The nozzle sensor **52** and the flow front sensor **53** may sense the presence of thermoplastic material optically, pneumatically, electrically, ultrasonically, mechanically or otherwise by sensing changes due to the arrival of the flow front of the thermoplastic material. The linear transducer may measure linear movement mechanically, optically, pneumatically, magnetically, electrically, ultrasonically, or the linear transducer may use any other method of measuring linear movement. When pressure or temperature of the thermoplastic material is measured by the nozzle sensor **52**, the nozzle sensor **52** may send a signal indicative of the pressure or the temperature to the controller **50** to provide a target pressure for the controller **50** to maintain in the mold cavity **32** (or in the nozzle **26**) as the fill is completed. This signal may generally be used to control the molding process, such that variations in material viscosity, mold temperatures, melt temperatures, and other variations influencing filling rate, are adjusted by the controller **50**. These adjustments may be made immediately during the molding cycle, or corrections can be made in subsequent cycles. Furthermore, several signals may be averaged over a number of cycles and then used to make adjustments to the molding process by the controller **50**. The controller **50** may be connected to the nozzle sensor **52**, the flow front sensor **53**, the screw control **36**, and/or the linear transducer **56** via wired connections **54**, **55**, **56**, **59**, respectively. In other embodiments, the controller **50** may be connected to the nozzle sensors **52**, to the flow front sensor **53**, to the screw control **56**, and to the linear transducer **57** via a wireless connection, a mechanical connection, a hydraulic connection, a pneumatic connection, or any other type of wired or wireless communication connection known to those having ordinary skill in the art that will allow the controller **50** to communicate with the sensors **52**, **53**, **57** and/or to send a control signal to the screw control **36** or any other component of the injection molding machine.

In the embodiment of FIG. **1**, the nozzle sensor **52** is a pressure sensor that measures (directly or indirectly) melt pressure of the molten thermoplastic material **24** in vicinity of the nozzle **26**. The nozzle sensor **52** generates an electrical signal that is transmitted to the controller **50**. The controller **50** then commands the screw control **36** to advance the screw **22** at a rate that maintains a desired melt pressure of the molten thermoplastic material **24** in the nozzle **26**. This is known as a pressure controlled process. While the nozzle sensor **52** may directly measure the melt pressure, the nozzle sensor **52** may also indirectly measure the melt pressure by measuring other characteristics of the molten thermoplastic material **24**, such as temperature, viscosity, flow rate, etc, which are indicative of melt pressure. Likewise, the nozzle sensor **52** need not be located directly in the nozzle **26**, but rather the nozzle sensor **52** may be located at any location within the injection system **12** or mold **28** that is fluidly connected with the nozzle **26**. If the nozzle sensor **52** is not located within the nozzle **26**, appropriate correction factors may be applied to the measured characteristic to calculate an estimate of the melt pressure in the nozzle **26**. The nozzle sensor **52** need not be in direct contact with the injected fluid and may alternatively be in dynamic communication with the fluid and able to sense the pressure of the fluid and/or other fluid characteristics. If the nozzle sensor **52** is not located within the nozzle **26**, appropriate correction factors may be applied to the measured characteristic to calculate the melt pressure in the nozzle **26**. In yet other embodiments, the nozzle sensor **52** need not be disposed at a location that is fluidly connected with the nozzle. Rather, the nozzle sensor **52** could measure clamping force generated by the clamping system **14** at a mold parting line between the first and second mold parts **25**, **27**. In one aspect the controller **50** may maintain the pressure according to the input from nozzle sensor **52**. Alternatively, the sensor could measure an electrical power demand by an electric press, which may be used to calculate an estimate of the pressure in the nozzle **26**.

Although an active, closed loop controller **50** is illustrated in FIG. **1**, other pressure regulating devices may be used instead of the closed loop controller **50**. For example, a pressure regulating valve (not shown) or a pressure relief valve (not shown) may replace the controller **50** to regulate the melt pressure of the molten thermoplastic material **24**. More specifically, the pressure regulating valve and pressure relief valve can prevent overpressurization of the mold **28**. Another alternative mechanism for preventing overpressurization of the mold **28** is an alarm that is activated when an overpressurization condition is detected.

Turning now to FIG. **2**, an example molded part **100** is illustrated. The molded part **100** is a thin-walled part. Molded parts are generally considered to be thin-walled when a length of a flow channel L divided by a thickness of the flow channel T is greater than 100 (i.e., L/T>100), but less than 1000. For mold cavities having a more complicated geometry, the L/T ratio may be calculated by integrating the T dimension over the length of the mold cavity **32** from the gate **30** to the end of the mold cavity **32**, and determining the longest length of flow from the gate **30** to the end of the mold cavity **32**. The L/T ratio can then be determined by dividing the longest length of flow by the average part thickness. In the case where a mold cavity **32** has more than one gate **30**, the L/T ratio is determined by integrating L and T for the portion of the mold cavity **32** filled by each individual gate and the overall L/T ratio for a given mold cavity is the highest L/T ratio that is calculated for any of the gates. In some injection molding industries, thin-walled parts may be defined as parts having an L/T>100, or having an L/T>200, but <1000. The length of the flow channel L is the longest flow length as measured from the gate **30** to the end **104** of the mold cavity. Thin-walled parts are especially prevalent in the consumer products industry.

High L/T ratio parts are commonly found in molded parts having average thicknesses less than about 10 mm. In consumer products, products having high L/T ratios generally have an average thickness of less than about 5 mm. For example, while automotive bumper panels having a high L/T ratio generally have an average thickness of 10 mm or less, tall drinking glasses having a high L/T ratio generally have an average thickness of about 5 mm or less, containers (such as tubs or vials) having a high L/T ratio generally have an average thickness of about 3 mm or less, bottle cap enclosures having a high L/T ratio generally have an average thickness of about 2 mm or less, and individual toothbrush bristles having a high L/T ratio generally have an average thickness of about 1 mm or less. The low constant pressure injection molding processes and devices disclosed herein are particularly advantageous for parts having a thickness of 5 mm or less and the disclosed processes and devices are more advantageous for thinner parts.

Thin-walled parts with high L/T ratios present certain obstacles in injection molding. For example, the thinness of the flow channel tends to cool the molten thermoplastic material before the material reaches the flow channel end **104**. When this happens, the thermoplastic material freezes off and no longer flows, which results in an incomplete part. To overcome this problem, traditional injection molding machines inject the molten thermoplastic material at very high pressures, typically greater than 15,000 psi, so that the molten thermoplastic material rapidly fills the mold cavity before having a chance to cool and freeze off. This is one reason that manufacturers of the thermoplastic materials teach injecting at very high pressures. Another reason traditional injection molding machines inject at high pressures is the increased shear, which increases flow characteristics, as discussed above. These very high injection pressures require the use of very hard materials to form the mold **28** and the feed system, among other things. Moreover, the thin walled parts may include one or more special features **105**, such as a living hinge, a filament, a closure, a dispenser, a spout, a bellows, and an actuator, that must be filled before the material freezes.

When filling at a substantially constant pressure (during an injection molding cycle), it was generally thought that the filling rates would need to be reduced relative to conventional filling methods. This means the polymer would be in contact with the cool molding surfaces for longer periods before the mold would completely fill. Thus, more heat would need to be removed before filling, and this would be expected to result in the material freezing off before the mold is filled. It has been unexpectedly discovered that the thermoplastic material will flow when subjected to substantially constant pressure conditions, during an injection molding cycle, despite a portion of the mold cavity being below the no-flow temperature of the thermoplastic material. It would be generally expected by one of ordinary skill in the art that such conditions would cause the thermoplastic material to freeze and plug the mold cavity rather than continue to flow and fill the entire mold cavity. Without intending to be bound by theory, it is believed that the substantially constant pressure conditions, during an injection molding cycle, of embodiments of the disclosed method and device allow for dynamic flow conditions (i.e., constantly moving melt front) throughout the entire mold cavity during filling. There is no hesitation in the flow of the molten thermoplastic material as it flows to fill the mold cavity and, thus, no opportunity for freeze-off of the flow despite at least a portion of the mold cavity being below the no-flow temperature of the thermoplastic material.

Additionally, it is believed that as a result of the dynamic flow conditions, the molten thermoplastic material is able to maintain a temperature higher than the no-flow temperature, despite being subjected to such temperatures in the mold cavity, as a result of shear heating. It is further believed that the dynamic flow conditions interfere with the formation of crystal structures in the thermoplastic material as it begins the freezing process. Crystal structure formation increases the viscosity of the thermoplastic material, which can prevent suitable flow to fill the cavity. The reduction in crystal structure formation and/or crystal structure size can allow for a decrease in the thermoplastic material viscosity as it flows into the cavity and is subjected to the low temperature of the mold that is below the no-flow temperature of the material.

The disclosed low constant pressure injection molding methods and systems may use a sensor (such as the nozzle sensor **52**, the flow front sensor **53**, or the linear transducer **57** in FIG. **1** above) located within the mold cavity or proximate the mold cavity to monitor changes in material viscosity, changes in material temperature, and/or changes in other material properties. Measurements from these sensors may be communicated to the controller **50** to allow the controller **50** to correct the process in real time to ensure the melt front pressure is relieved prior to the melt front reaching the end of the mold cavity, which can cause flashing of the mold, and another pressure and power peak. Moreover, the controller **50** may use the sensor measurements to adjust the peak power and peak flow rate points in the process, so as to achieve consistent processing conditions. In addition to using the sensor measurements to fine tune the process in real time during the current injection cycle, the controller **50** may also to adjust the process over time (e.g., over a plurality of injection cycles). In this way, the current injection cycle can be corrected based on measurements occurring during one or more cycles at an earlier point in time. In one embodiment, sensor readings can be averaged over many cycles so as to achieve process consistency.

In various embodiments, the mold can include a cooling system that maintains the entire mold cavity at a temperature below the no-flow temperature. For example, even surfaces of the mold cavity which contact the shot comprising molten thermoplastic material can be cooled to maintain a lower temperature. Any suitable cooling temperature can be used. For example, the mold can be maintained substantially at room temperature. Incorporation of such cooling systems can advantageously enhance the rate at which the as-formed injection molded part is cooled and ready for ejection from the mold.

Thermoplastic Material:

A variety of thermoplastic materials can be used in the low constant pressure injection molding methods and devices of the disclosure. In one embodiment, the molten thermoplastic material has a viscosity, as defined by the melt flow index of about 0.1 g/10 min to about 500 g/10 min, as measured by ASTM D1238 performed at temperature of about 230 C with a 2.16 kg weight. For example, for polypropylene the melt flow index can be in a range of about 0.5 g/10 min to about 200 g/10 min. Other suitable melt flow indexes include about 1 g/10 min to about 400 g/10 min, about 10 g/10 min to about 300 g/10 min, about 20 to about 200 g/10 min, about 30 g/10 min to about 100 g/10 min, about 50 g/10 min to about 75 g/10 min, about 0.1 g/10 min to about 1 g/10 min, or about 1 g/10 min to about 25 g/10 min. The MFI of the material is selected based on the application and use of the molded article. For examples, thermoplastic materials with an MFI of 0.1 g/10 min to about 5 g/10 min may be suitable for use as preforms for Injection Stretch Blow Molding (ISBM) applications. Thermoplastic materials with an MFI of 5 g/10 min to about 50 g/10 min may be suitable for use as caps and closures for packaging articles. Thermoplastic materials with an MFI of 50 g/10 min to about 150 g/10 min may be suitable for use in the manufacture of buckets or tubs. Thermoplastic materials with an MFI of 150 g/10 min to about 500 g/10 min may be suitable for molded articles that have extremely high L/T ratios such as a thin plate. Manufacturers of such thermoplastic materials generally teach that the materials should be injection molded using melt pressures in excess of 6000 psi, and often in great excess of 6000 psi. Contrary to conventional teachings regarding injection molding of such thermoplastic materials, embodiments of the low constant pressure injection molding method and device of the disclosure advantageously allow for forming quality injection molded parts using such thermoplastic materials and processing at melt pressures below 15,000 psi, and possibly well below 15,000 psi.

The thermoplastic material can be, for example, a polyolefin. Exemplary polyolefins include, but are not limited to, polypropylene, polyethylene, polymethylpentene, and polybutene-1. Any of the aforementioned polyolefins could be sourced from bio-based feedstocks, such as sugarcane or other agricultural products, to produce a bio-polypropylene or bio-polyethylene. Polyolefins advantageously demonstrate shear thinning when in a molten state. Shear thinning is a reduction in viscosity when the fluid is placed under compressive stress. Shear thinning can beneficially allow for the flow of the thermoplastic material to be maintained throughout the injection molding process. Without intending to be bound by theory, it is believed that the shear thinning properties of a thermoplastic material, and in particular polyolefins, results in less variation of the materials viscosity when the material is processed at constant pressures. As a result, embodiments of the method and device of the disclosure can be less sensitive to variations in the thermoplastic material, for example, resulting from colorants and other additives as well as processing conditions. This decreased sensitivity to batch-to-batch variations of the properties thermoplastic material can also advantageously allow post-industrial and post consumer recycled plastics to be processed using embodiments of the method and the device of the disclosure. Post-industrial, post consumer recycled plastics are derived from end products that have completed their life cycle as a consumer item and would otherwise have been disposed of as a solid waste product. Such recycled plastic, and blends of thermoplastic materials, inherently have significant batch-to-batch variation of their material properties.

The thermoplastic material can also be, for example, a polyester. Exemplary polyesters include, but are not limited to, polyethylene terphthalate (PET). The PET polymer could be sourced from bio-based feedstocks, such as sugarcane or other agricultural products, to produce a partially or fully bio-PET polymer. Other suitable thermoplastic materials include copolymers of polypropylene and polyethylene, and polymers and copolymers of thermoplastic elastomers, polyester, polystyrene, polycarbonate, poly(acrylonitrile-butadiene-styrene), poly(lactic acid), bio-based polyesters such as poly(ethylene furanate) polyhydroxyalkanoate, poly(ethylene furanoate), (considered to be an alternative to, or drop-in replacement for, PET), polyhydroxyalkanoate, polyamides, polyacetals, ethylene-alpha olefin rubbers, and styrene-butadiene-styrene block copolymers. The thermoplastic material can also be a blend of multiple polymeric and non-polymeric materials. The thermoplastic material can be, for example, a blend of high, medium, and low molecular polymers yielding a multi-modal or bi-modal blend. The multi-modal material can be designed in a way that results in a thermoplastic material that has superior flow properties yet has satisfactory chemo/physical properties. The thermoplastic material can also be a blend of a polymer with one or more small molecule additives. The small molecule could be, for example, a siloxane or other lubricating molecule that, when added to the thermoplastic material, improves the flowability of the polymeric material.

Other additives may include inorganic fillers such calcium carbonate, calcium sulfate, talcs, clays (e.g., nanoclays), aluminum hydroxide, CaSiO3, glass formed into fibers or microspheres, crystalline silicas (e.g., quartz, novacite, crystallobite), magnesium hydroxide, mica, sodium sulfate, lithopone, magnesium carbonate, iron oxide; or, organic fillers such as rice husks, straw, hemp fiber, wood flour, or wood, bamboo or sugarcane fiber.

Other suitable thermoplastic materials include renewable polymers such as nonlimiting examples of polymers produced directly from organisms, such as polyhydroxyalkanoates (e.g., poly(beta-hydroxyalkanoate), poly(3-hydroxybutyrate-co-3-hydroxyvalerate, NODAX (Registered Trademark)), and bacterial cellulose; polymers extracted from plants, agricultural and forest, and biomass, such as polysaccharides and derivatives thereof (e.g., gums, cellulose, cellulose esters, chitin, chitosan, starch, chemically modified starch, particles of cellulose acetate), proteins (e.g., zein, whey, gluten, collagen), lipids, lignins, and natural rubber; thermoplastic starch produced from starch or chemically starch and current polymers derived from naturally sourced monomers and derivatives, such as bio-polyethylene, bio-polypropylene, polytrimethylene terephthalate, polylactic acid, NYLON 11, alkyd resins, succinic acid-based polyesters, and bio-polyethylene terephthalate.

The suitable thermoplastic materials may include a blend or blends of different thermoplastic materials such in the examples cited above. As well the different materials may be a combination of materials derived from virgin bio-derived or petroleum-derived materials, or recycled materials of bio-derived or petroleum-derived materials. One or more of the thermoplastic materials in a blend may be biodegradable. And for non-blend thermoplastic materials that material may be biodegradable.

Exemplary thermoplastic resins together with their recommended operating pressure ranges are provided in the following table:

Material	Full Name	Injection Pressure Range (PSI)	Company	Material Brand Name
pp	Polypropylene	10000-15000	RTP Imagineering Plastics	RTP 100 series Polypropylene
Nylon		10000-18000	RTP Imagineering Plastics	RTP 200 series Nylon
ABS	Acrylonitrile Butadiene Styrene	8000-20000	Marplex	Astalac ABS
PET	Polyester	5800-14500	Asia International	AIE PET 401F
Acetal Copolymer		7000-17000	API Kolon	Kocetal
PC	Polycarbonate	10000-15000	RTP Imagineering Plastics	RTP 300 series Polycarbonate
PS	Polystyrene	10000-15000	RTP Imagineering Plastics	RTP 400 series
SAN	Styrene Acrylonitrile	10000-15000	RTP Imagineering Plastics	RTP 500 series
PE	LDPE & HDPE	10000-15000	RTP Imagineering Plastics	RTP 700 Series
TPE	Thermoplastic Elastomer	10000-15000	RTP Imagineering Plastics	RTP 1500 series
PVDF	Polyvinylidene Fluoride	10000-15000	RTP Imagineering Plastics	RTP 3300 series
PTI	Polytrimethylene Terephthalate	10000-15000	RTP Imagineering Plastics	RTP 4700 series
PBT	Polybutylene Terephthalate	10000-15000	RTP Imagineering Plastics	RTP 1000 series
PLA	Polylactic Acid	8000-15000	RTP Imagineering Plastics	RTP 2099 series

While more than one of the embodiments involves filling substantially the entire mold cavity with the shot comprising the molten thermoplastic material while maintaining the melt pressure of the shot comprising the molten thermoplastic material at a substantially constant pressure, during the injection molding cycle, specific thermoplastic materials benefit from the invention at different constant pressures. Specifically: PP, nylon, PC, PS, SAN, PE, TPE, PVDF, PTI, PBT, and PLA at a substantially constant pressure of less than 10000 psi; ABS at a substantially constant pressure of less than 8000 psi; PET at a substantially constant pressure of less than 5800 psi; Acetal copolymer at a substantially constant pressure of less than 7000 psi; plus poly(ethylene furanate) polyhydroxyalkanoate, polyethylene furanoate (aka PEF) at substantially constant pressure of less than 10000 psi, or 8000 psi, or 7000 psi or 6000 psi, or 5800 psi.

As described in detail above, embodiments of the disclosed low constant pressure injection molding method and device can achieve one or more advantages over conventional injection molding processes. For example, embodiments include a more cost effective and efficient process that eliminates the need to balance the pre-injection pressures of the mold cavity and the thermoplastic materials, a process that allows for use of atmospheric mold cavity pressures and, thus, simplified mold structures that eliminate the necessity of pressurizing means, the ability to use lower hardness, high thermal conductivity mold cavity materials that are more cost effective and easier to machine, a more robust processing method that is less sensitive to variations in the temperature, viscosity, and other material properties of the thermoplastic material, and the ability to produce quality injection molded parts at substantially constant pressures without premature hardening of the thermoplastic material in the mold cavity and without the need to heat or maintain constant temperatures in the mold cavity.

Turning now to FIG. **3**, a typical pressure-time curve for a conventional high variable pressure injection molding process is illustrated by the dashed line **200**. By contrast, a pressure-time curve for the disclosed low constant pressure injection molding machine is illustrated by the solid line **210**. In the conventional case, melt pressure is rapidly increased to well over 15,000 psi and then held at a relatively high pressure, more than 15,000 psi, for a first period of time **220**. The first period of time **220** is the fill time in which molten plastic material flows into the mold cavity. Thereafter, the melt pressure is decreased and held at a lower, but still relatively high pressure, typically 10,000 psi or more, for a second period of time **230**. The second period of time **230** is a packing time in which the melt pressure is maintained to ensure that all gaps in the mold cavity are back filled. After packing is complete, the pressure may optionally be dropped again for a third period of time **232**, which is the cooling time. The mold cavity in a conventional high variable pressure injection molding system is packed from the end of the flow channel back to towards the gate. The material in the mold typically freezes off near the end of the cavity, then completely frozen off region of material progressively moves toward the gate location, or locations. As a result, the plastic near the end of the mold cavity is packed for a shorter time period and with reduced pressure, than the plastic material that is closer to the gate location, or locations. Part geometry, such as very thin cross sectional areas midway between the gate and end of mold cavity, can also influence the level of packing pressure in regions of the mold cavity. Inconsistent packing pressure may cause inconsistencies in the finished product, as discussed above. Moreover, the conventional packing of plastic in various stages of solidification results in some non-ideal material properties, for example, molded-in stresses, sink, and non-optimal optical properties.

The low constant pressure injection molding system, on the other hand, injects the molten plastic material into the mold cavity at a substantially constant pressure for a fill time period **240**. The injection pressure in the example of FIG. **3** is less than 6,000 psi. However, other embodiments may use higher pressures. After the mold cavity is filled, the low constant pressure injection molding system gradually reduces pressure over a second time period **242** as the molded part is cooled. By using a substantially constant pressure during the injection molding cycle, the molten thermoplastic material maintains a continuous melt flow front that advances through the flow channel from the gate towards the end of the flow channel. In other words, the molten thermoplastic material remains moving throughout the mold cavity, which prevents premature freeze off. Thus, the plastic material remains relatively uniform at any point along the flow channel, which results in a more uniform and consistent finished product. By filling the mold with a relatively uniform pressure, the finished molded parts form crystalline structures that may have better mechanical and optical properties than conventionally molded parts. Moreover, the parts molded at constant pressures exhibit different characteristics than skin layers of conventionally molded parts. As a result, parts molded under constant pressure may have better optical properties than parts of conventionally molded parts.

Turning now to FIG. **4**, the various stages of fill are broken down as percentages of overall fill time. For example, in an conventional high variable pressure injection molding process, the fill period **220** makes up about 10% of the total fill time, the packing period **230** makes up about 50% of the total fill time, and the cooing period **232** makes up about 40% of the total fill time. On the other hand, in the low constant pressure injection molding process, the fill period **240** makes up about 90% of the total fill time while the cooling period **242** makes up only about 10% of the total fill time. The low constant pressure injection molding process needs less cooling time because the molten plastic material is cooling as it is flowing into the mold cavity. Thus, by the time the mold cavity is filled, the molten plastic material has cooled significantly, although not quite enough to freeze off in the center cross section of the mold cavity, and there is less total heat to remove to complete the freezing process. Additionally, because the molten plastic material remains liquid throughout the fill, and packing pressure is transferred through this molten center cross section, the molten plastic material remains in contact with the mold cavity walls (as opposed to freezing off and shrinking away). As a result, the low constant pressure injection molding process described herein is capable of filling and cooling a molded part in less total time than in a conventional injection molding process.

In the disclosed low constant pressure injection molding method and device for molding a high L/T part, the part is molded by injecting a molten thermoplastic polymer into a mold cavity at an increasing flow rate to achieve a desired injection pressure and then decreasing the flow rate over time to maintain a substantially constant injection pressure. The low constant pressure injection molding method and device are particularly advantageous when molding thinwall parts (e.g., parts having an L/T ratio>100<1000) and when using shot sizes of between 0.1 g and 100 g. It is especially advantageous that the maximum flow rate occur within the first 30% of cavity fill, preferably within the first 20% of cavity fill, and even more preferably within the first 10% of cavity fill. By adjusting the filling pressure profile the maximum flow rate occurs within these preferred ranges of cavity fill, the molded part will have at least some of the physical advantages described above (e.g., better strength, better optical properties, etc.) because the crystalline structure of the molded part is different from a conventionally molded part. Moreover, because high L/T products are thinner, these products require less pigment to impart a desired color to the resulting product. Furthermore, in no-pigment parts, the parts will have less visible deformities due to the more consistent molding conditions. Using less or no pigment saves costs.

Alternatively, the peak power may be adjusted to maintain a substantially constant injection pressure. More specifically, the filling pressure profile may be adjusted to cause the peak power to occur in the first 30% of the cavity fill, preferably in the first 20% of the cavity fill, and even more preferably in the first 10% of the cavity fill. Adjusting the process to cause the peak power to occur within the preferred ranges, and then to have a decreasing power throughout the remainder of the cavity fill results in the same benefits for the molded part that were described above with respect to adjusting peak flow rate. Moreover, adjusting the process in the manner described above is particularly advantageous for thinwall parts (e.g., L/T ratio>100<1000) and for shot sizes of between 0.1 g and 100 g).

Turning now to FIGS. **5**A-**5**D and FIGS. **6**A-**6**D a portion of a mold cavity as it is being filled by a conventional injection molding machine (FIGS. **5**A-**5**D) and as it is being filled by a substantially constant pressure injection molding machine (FIGS. **6**A-**6**D) is illustrated.

As illustrated in FIGS. **5**A-**5**D, as the conventional injection molding machine begins to inject molten thermoplastic material **24** into a mold cavity **32** through the gate **30**, the high injection pressure tends to inject the molten thermoplastic material **24** into the mold cavity **32** at a high rate of speed, which causes the molten thermoplastic material **24** to flow in laminates **31**, most commonly referred to as laminar flow (FIG. **5**A). These outermost laminates **31** adhere to walls of the mold cavity and subsequently cool and freeze, forming a frozen boundary layer **33** (FIG. **5**B), before the mold cavity **32** is completely full. As the thermoplastic material freezes, however, it also shrinks away from the wall of the mold cavity **32**, leaving a gap **35** between the mold cavity wall and the boundary layer **33**. This gap **35** reduces cooling efficiency of the mold. Molten thermoplastic material **24** also begins to cool and freeze in the vicinity of the gate **30**, which reduces the effective cross-sectional area of the gate **30**. In order to maintain a constant volumetric flow rate, the conventional injection molding machine must increase pressure to force molten thermoplastic material through the narrowing gate **30**. As the thermoplastic material **24** continues to flow into the mold cavity **32**, the boundary layer **33** grows thicker (FIG. **5**C). Eventually, the entire mold cavity **32** is substantially filled by thermoplastic material that is frozen (FIG. **5**D). At this point, the conventional injection molding machine must maintain a packing pressure to push the receded boundary layer **33** back against the mold cavity **32** walls to increase cooling.

A low constant pressure injection molding machine, on the other hand, flows molten thermoplastic material into a mold cavity **32** with a constantly moving flow front **37** (FIGS. **6**A-**6**D). The thermoplastic material **24** behind the flow front **37** remains molten until the mold cavity **37** is substantially filled (i.e., 99% or more filled) before freezing. As a result, there is no reduction in effective cross-sectional area of the gate **30**, which may be between 70% and 100%, preferably between 80% and 90%, of the nominal wall thickness of the molded part. Moreover, because the thermoplastic material **24** is molten behind the flow front **37**, the thermoplastic material **24** remains in contact with the walls of the mold cavity **32**. As a result, the thermoplastic material **24** is cooling (without freezing) during the fill portion of the molding process. Thus, the cooling portion of the disclosed low constant pressure injection molding process need not be as long as a conventional process.

Because the thermoplastic material remains molten and keeps moving into the mold cavity **32**, less injection pressure is required than in conventional molds. In one embodiment, the injection pressure may be 6,000 psi or less. As a result, the injection systems and clamping systems need not be as powerful. For example, the disclosed low constant pressure injection molding devices may use clamps requiring lower clamping forces, and a corresponding lower clamping power source. Moreover, the disclosed low constant pressure injection molding machines, because of the lower power requirements, may employ electric presses, which are generally not powerful enough to use in conventional class 101 and 102 injection molding machines that mold thinwall parts at high variable pressures. Even when electric presses are sufficient to use for some simple, molds with few mold cavities, the process may be improved with the disclosed low constant pressure injection molding methods and devices as smaller, less expensive electric motors may be used. The disclosed low constant pressure injection molding machines may comprise one or more of the following types of electric presses, a direct servo drive motor press, a dual motor belt driven press, a dual motor planetary gear press, and a dual motor ball drive press having a power rating of 200 HP or less.

Turning now to FIG. **7**, operation of an example molding cycle **1000** for the low constant pressure injection molding process is illustrated. The molding cycle **1000** may be carried out on a low constant pressure injection molding machine constructed in accordance with the disclosure, for example, on the low constant pressure injection molding machine of FIG. **1**. More specifically, the example molding cycle **1000** may be carried out on a low constant pressure injection molding machine having a mold including a first mold side and a second mold side, at least one of the first mold side and the second mold side having an average thermal conductivity of more than 51.9 W/m-° C. (30 BTU/HR FT ° F.) and less than or equal to 385.79 W/m-° C. (223 BTU/HR FT ° F.), and a mold cavity that is formed between the first mold side and the second mold side. In some preferred embodiments, both the first and second mold side may have an average thermal conductivity of more than 51.9 W/m-° C. (30 BTU/HR FT ° F.) and less than or equal to 385.79 W/m-° C. (223 BTU/HR FT ° F.).

Some preferred materials for manufacturing the first and/or second mold sides include aluminum (for example, 2024 aluminum, 2090 aluminum, 2124 aluminum, 2195 aluminum, 2219 aluminum, 2324 aluminum, 2618 aluminum, 5052 aluminum, 5059 aluminum, aircraft grade aluminum, 6000 series aluminum, 6013 aluminum, 6056 aluminum, 6061 aluminum, 6063 aluminum, 7000 series aluminum, 7050 aluminum, 7055 aluminum, 7068 aluminum, 7075 aluminum, 7076 aluminum, 7150 aluminum, 7475 aluminum, QC-10, Alumold™, Hokotol™, Duramold 2™, Duramold 5™, and Alumec 99™), BeCu (for example, C17200, C 18000, C61900, C62500, C64700, C82500, Moldmax LH™, Moldmax HH™, and Protherm™), Copper, and any alloys of aluminum (e.g., Beryllium, Bismuth, Chromium, Copper, Gallium, Iron, Lead, Magnesium, Manganese, Silicon, Titanium, Vanadium, Zinc, Zirconium), any alloys of copper (e.g., Magnesium, Zinc, Nickel, Silicon, Chromium, Aluminum, Bronze). These materials may have Rockwell C (Rc) hardnesses of between 0.5 Rc and 20 Rc, preferably between 2 Rc and 20 Rc, more preferably between 3 Rc and 15 Rc, and more preferably between 4 Rc and 10 Rc. While these materials may be softer than tool steels, the thermal conductivity properties are more desirable. The disclosed low constant pressure injection molding methods and devices advantageously operate under molding conditions that allow molds made of these softer, higher thermal conductivity, materials to extract useful lives of more than 1 million cycles, preferably between 1.25 million cycles and 10 million cycles, and more preferably between 2 million cycles and 5 million cycles.

Initially, molten thermoplastic material is advanced into a mold cavity that defines a thin-walled part (e.g., $100<L/T<1000$) at **1110**. A shot of molten thermoplastic material may be between 0.5 g and 100 g and may be advanced through three or fewer gates into the mold cavity. In some cases one or more of the three of fewer gates may have a cross-sectional area that is between 70% and 100% of a nominal wall thickness of a part that is formed in the mold cavity, and preferably between 80% and 90% of the nominal wall thickness. In some examples, this percentage may correspond to a gate size of between 0.5 mm and 10 mm.

Molten thermoplastic material is advanced into the mold cavity until the mold cavity is substantially filled at **1112**. The mold cavity may be substantially filled when the mold cavity is more than 90% filled, preferably more than 95% filled and more preferably more than 99% filled. After the mold cavity is substantially filled, the molten thermoplastic material is cooled at **1114** until the molten thermoplastic material is substantially frozen or solidified. The molten thermoplastic material may be actively cooled with a cooling liquid flowing through at least one of the first and second mold sides, or passively cooled through convection and conduction to the atmosphere.

After the thermoplastic material is cooled, the first and second mold sides may be separated to expose the cooled thermoplastic material at **1116**. The cooled thermoplastic material (in the form of the molded part) may be removed from the mold at **1118**. The thermoplastic material may be removed by, for example, ejection, dumping, extraction (manually or via an automated process), pulling, pushing, gravity, or any other method of separating the cooled thermoplastic material from the first and second mold sides.

After the cooled thermoplastic material is removed from the first and second mold sides, the first and second mold sides may be closed, reforming the mold cavity, at **1120**, which prepares the first and second mold sides to receive a new shot of molten thermoplastic material, thereby completing a single mold cycle. Cycle time **1001** is defined as a single iteration of the molding cycle **1000**. A single molding cycle may take between 2 seconds and 15 seconds, preferably between 8 seconds and 10 seconds, depending on the part size and material.

All injection molding processes are susceptible to variations in the viscosity of the molten plastic material. Variations in the viscosity of the molten plastic material may cause imperfections in the molded part, such as insufficient material (e.g., short shot), and flashing. Any number of factors can cause the viscosity of the molten plastic material to vary. For example, changes in ambient temperature or pressure, the addition of a colorant, changes in shear conditions between the feed system and the last cavity location to fill with molten plastic material (otherwise known as the "end of fill location"), viscosity variations in the virgin plastic material itself, and changes in other conditions all may cause the viscosity of the molten plastic material to change. As viscosity of the molten plastic material changes, pressure required to force the molten plastic into the mold will also change. For example, if viscosity increases, pressure required to force the polymer into the mold cavity will increase because the polymer is thicker and harder to move into the mold cavity. On the other hand, as viscosity decreases, pressure required force the polymer into the mold cavity will decrease because the polymer is thinner and easier to move into the mold cavity. If no adjustments are made to the injection pressure or the cycle time, the molded part may have flaws. Current injection molding machines and processes have molding cycles that are time-based. In other words, the molding cycle is controlled by time, among other factors, as the injection molding cycle is ended at a predetermined time. As a result, changes in viscosity to the molten plastic material may cause the molten plastic material to reach in end of the mold cavity at a time that is different from the predetermined time.

Turning now to FIG. **8**, a pressure versus time graph is illustrated for a single injection molding cycle. During an initial phase of the injection molding cycle pressure rapidly increases to a predetermined target value **1210** (e.g., a "fill pressure"), where the pressure is held as the mold cavity is filled. When molten plastic material nears the end of the mold cavity **32**, as indicated by the flow front sensor **53** (FIG. **1**), at a first time t_t (or $t_{transducer}$) **1212**, pressure is reduced at **1214** to a lower pressure (e.g., a "pack and hold pressure") as the material in the mold cavity **32** cools. At a second time t_s (or t_{step}) **1216**, which is a total cycle time from initiation of the filling sequence to an end of the filling cycle where the mold is opened in the molded part is ejected from the mold cavity **32**.

Changes in viscosity of the molten plastic material may affect the time at which the molten plastic material reaches the end of the mold cavity **32** or the end of fill location in the mold cavity at t_s. For example, if viscosity of the molten plastic material increases, (with the possibility of a "short shot"), then the molten plastic material may be maintained at the fill pressure for a longer time, as illustrated by dashed line **1220***a*. In this example, the flow front sensor **53** may detect the molten plastic material at a time that is later than a predetermined time. A predetermined time for the molten plastic to reach the flow front sensor may be calculated or derived experimentally for ideal conditions and constant viscosity for the molten plastic material. On the other hand, if viscosity of the molten plastic material decreases, (with the possibility of "flashing"), then the molten plastic material may be maintained at the fill pressure for a shorter time, as illustrated by the dashed line **1220***b*. In this example, the flow front sensor **53** may detect molten plastic material at a time t_t that is earlier than the predetermined time.

In the case of a pressure controlled filling process, an optimal filling pressure profile can be determined experimentally. This optimal pressure profile establishes the optimal plastic pressures for a nominal polymer at each instant of the filling cycle. Polymer pressure is sensed at a location in the polymer flow channel prior to the mold cavity. In one example, polymer pressure may be sensed by the nozzle sensor **52**. However, the polymer pressure may be sensed at any location upstream of the gate. A nominal flow rate may be assigned to each instant during the filling cycle by calculating or directly measuring the polymer flow rate during the filling cycle. Furthermore, force required to move a given volume of the polymer through the feed system and in to the mold cavity may be determined for the optimal filling pressure profile through experimentation or calculation.

For each filling cycle, the controller **50** may compare the nominal (or optimal) force required to move polymer through the system and the actual force required to move a given volume of polymer through the feed system during the filling cycle. If the actual force is higher than the nominal force, then material flowability has increased. As a result, a corresponding and proportional increase to the filling force is required to generate the optimal polymer flow rate profile.

Polymer pressure, at any given point in the system, is an indication of a magnitude of force that is required to move polymer through the system. Additionally, polymer pressure, at any given point in the system, is directly proportional to a magnitude of force that is required to move polymer through the system. As a result, polymer pressure may be used to balance or offset shrinkage forces in the polymer as it cools in the mold cavity.

For a hydraulic injection molding press, a proportional valve may be used to regulate the flow of hydraulic fluid to the system acting upon the injection screw **22**. An electronic control signal may be sent to the proportional valve, which causes the proportional valve to move in response to the control signal. When the voltage of the control signal to the proportional valve increases, the proportional valve moves to deliver more hydraulic pressure to the reciprocating screw **22**, thereby forcing more polymer through the feed system. As-polymer viscosity changes, the resistance to flow through the system will change, as discussed above. Thus, to maintain the polymer flow rate through the feed system at a rate that is equivalent to the flow rate for a nominal fluid viscosity material, the voltage of the control signal to the proportional valve must be changed. This same relationship may be established for electric presses, where the voltage of the control signal changes amperage to a servo motor. Or for electric-hydraulic hybrid injection presses where separate, but synchronized, control signals are sent to electric servo drives and to a proportional valve.

Turning now to FIG. **9**A, a graph **1310** illustrates control signal response (in voltage) from the controller to the proportional valve over time. The vertical axis of the graph **1312** corresponds to control signal voltage in millivolts and the horizontal axis of the graph **1314** corresponds to time in milliseconds. A ratio of the change in the voltage of the control signal to the proportional valve to the time period for the change may be used to control the injection process. This value can be expressed as a ratio of millivolts to time, for example, and is defined herein as the Flow Factor (FF). The Flow Factor ratio may be determined for an injection molding process for any molding machine, including hydraulic, electric, or any other molding machine. The Flow Factor (FF) may be mathematically represented by the following formula:

$$FF=(CS1-CS2)T;$$

wherein CS1 and CS2 are control signals (that may be measured, for example, in millivolts) that are measured at a distinct moments in time during the injection molding cycle.

While reference is made herein to a "first control signal" and a "second control signal," the control signal from the controller **50** to the proportional valve is a continuous signal, as illustrated in FIG. **9**A. However, this control signal may be measured at distinct moments in time (e.g., a first time t1 **1316** and a second time t2 **1318**) during the injection molding cycle to define the first and second control signals. The voltages measured at these distinct moments in time are referred to herein as the first control signal voltage **1320** and the second control signal voltage **1322**, respectively. While the control signals in the described embodiments are defined, at least in part, by electrical voltages, other control signal parameters may be used similarly. For example if the control signal were pneumatic in nature, the flow factor may be defined by the control signal parameter of pressure. Similarly, if the control signal were optical in nature, the flow factor may be defined by the control signal parameter of brightness or intensity. Those skilled in the art may select an appropriate control signal parameter given the nature of the control signal itself.

Preferred time increments for t1 and t2 may lie between 0.1 milliseconds and 10 milliseconds, preferably between 0.5 milliseconds and 5 milliseconds, more preferably between 0.75 milliseconds and 2 milliseconds, and even more preferably about 1 millisecond. Time periods in the disclosed ranges provide a very responsive control system that quickly adjusts the control signal in response to changes in flowability.

In the case of a pressure controlled process, such as the pressure controlled processes described herein, the controller **50** may adjust the flow of polymer material to reach a predetermined pressure set point. As flowability decreases, and corresponding resistances along the flow length drop, more flow is required to reach the pressure set point, and thus the actual FF_1 may be higher than the expected or optimal FF. This relationship may be used to detect, at any point, instantaneously or periodically, in an injection molding cycle, whether the system flowability has changed. This system flowability shift could be caused by any number of factors, including molecular weight distribution changes in the polymer, and shear or temperature changes. For example, if the actual FF is higher than the optimal FF, then the flowability has decreased. Similarly, if the actual FF is lower than the optimal FF, then flowability has increased. This change in FF is caused by the system attempting to maintain a predetermined pressure. If the flowability is lowered, the proportional valve must release additional hydraulic pressure to the system to force the higher viscosity material to reach the pre-determined pressure set point. Likewise, if the flowability is increased, then the proportional valve must release less hydraulic pressure to the system to force the lower viscosity material to reach the pre-determined pressure set point. The control response to increase or decrease polymer pressure could be linear or non-linear and may be based on dependent or independent system variables.

Furthermore, the difference between the actual FF and the optimal FF may be calibrated to the nominal viscosity of the polymer, such that a change the control signal is calibrated to a corresponding change in the flowabilty of molten plastic material, as measured in real time. Thus, this difference between the actual FF and the optimal FF, may be indexed relative to flowability. The actual FF may be compared to the optimal FF at any point in the process, and the difference may be used to adjust a target filling pressures for the remainder of the filling cycle. For example, if the FF is compared early in the cycle (e.g., the first 10% of the cycle), then the target pressure for the remainder of the cycle (e.g., the last 90%) may be adjusted upward or downward based on the comparison between the actual FF and the optimal FF. Moreover, the comparison between the actual FF and the optimal FF may be used to adjust the target pressure of a subsequent injection cycle, even if adjustment to the target pressure within the current injection cycle is made. By comparing the actual FF to the optimal FF, the target filling pressure may be adjusted intra cycle or inter cycle to account for changes in polymer flowability.

In some instances, a factor may be defined that incorporates the difference between first and second control signals as a ratio to the incremental movement of the injection unit (for example, as measured by the linear transducer **57** and representing a volume of material flow per unit of movement). Such a factor is further defined herein as a Viscosity Change Index (VCI). VCI takes in to account the influence of changes in the system Pressure (P), changes to polymer Volume (V), system Temperature (T), and material composition or molecular weight distribution (C). VCI is a function of the sum of the influences of P, V, T, and C in the total polymer flow system, and is represented by the formula:

$$VCI=f[\Delta P,\Delta V,\Delta T,\Delta C].$$

Or expressed as a measured variable:

$$VCI=(CS1-CS2)/S;$$

where CS1 is a first control signal, CS2 is a second control signal and S is a positional difference for a melt moving machine component, such as the injection screw **22**;
VCI may be used to control a process to compensate for changes in the flowability of the molten plastic material during an injection molding cycle of the injection molding system, thereby enabling instantaneous adjustments to the filling process to achieve the optimal polymer flow rate profile. Similar to FF above, changes in VCI indicate changes in flowability, as measured in real time, at any point in the filling cycle and thereafter may be used to increase or decrease filling pressure in response to the change.]

Turning now to FIG. **9**B, a graph **1350** illustrates control signal response (in voltage) from the controller to the proportional valve over time. The vertical axis of the graph **1352** corresponds to control signal voltage in milliamps and the horizontal axis of the graph **1354** corresponds to a distance movement of the melt moving machine component in microns.

The control signal may be measured at distinct moments in time (e.g., a first time t1 **1356** and a second time t2 **1358**) during the injection molding cycle. The voltages measured at these distinct moments in time are referred to herein as the first control signal voltage **1360** and the second control signal voltage **1362**, respectively. While the control signals in the described embodiments are defined, at least in part, by electrical voltages, other control signal parameters may be used similarly. For example if the control signal were pneumatic in nature, the flow factor may be defined by the control signal parameter of pressure. Similarly, if the control signal were optical in nature, the flow factor may be defined by the control signal parameter of brightness or intensity. Those skilled in the art may select an appropriate control signal parameter given the nature of the control signal itself. VCI acts as a "soft sensor" in the system, since it uses other sensors and measured variables to calculate a value corresponding to changes in polymer viscosity. FF may also be used as a "soft sensor" in the system. The VCI "soft sensor" may be used to determine changes in material flowability during the filling cycle and thus to enable instantaneous adjustments to the filling process to achieve the optimal polymer flow rate profile. Changes in VCI may indicate changes in the flowability of the molten plastic material at any point in the filling cycle, and then this value may be used to control filling pressure. VCI may be determined at a plurality of instantaneous points during the filling cycle, by comparing the ratio of the difference between CV1 and CV2, as a ratio to a 1 micron travel of the injection unit. If VCI has increased, then a corresponding control response is made to increase the target filling pressure for the next increment of fill to compensate for the shift in flowability. If VCI has decreased, then a corresponding control response is made to decrease the target filling pressure for the next increment of fill. The control response may be linear or non-linear and may be adjusted based on dependent or independent system variables.

For the purposes of controlling the injection molding process, it is possible to calculate VCI at any point in an injection molding cycle, and then to use VCI as a basis for a single adjustment to the target filling pressure for subsequent portions of the injection molding cycle. If VCI is calculated early in the injection molding cycle (e.g., the first 10% of the cycle), then the target filling pressure for the remainder of the injection molding cycle (e.g., the remaining 90% of the cycle) may be adjusted upward or downward based on the VCI calculation. Alternatively, the VCI calculation may be used to adjust a subsequent injection molding cycle, even if a target pressure of the current injection molding cycle is not adjusted. By calculating a VCI a control response may be made to increase or decrease filling pressure in real time. By calculating VCI (or FF) in real time, the disclosed system and method advantageously react nearly instantaneously to changes in system flowability and also adjust process variables quickly to compensate for any flowability changes for a current injection cycle as well as for subsequent injection cycles. The disclosed soft sensors may be incorporated into control logic that determines corrective inputs based on rates of change of the soft sensors, or differences between the soft sensor values and reference curves or data tables.

Injection pressure may also be adjusted on a continuous basis throughout the injection molding cycle. For example, when VCI is calculated at any point in the injection molding cycle the VCI may be fed forward and an adjustment in the target filling pressure may be made for the next increment of the injection molding cycle. For example, VCI may be calculated every 0.5 milliseconds and subsequent target filling pressures may be adjusted based on the immediately previous VCI (or an average of one or more previous VCIs). This process may be repeated throughout the injection molding cycle, thus controlling the process on a closed loop basis throughout the injection molding cycle. When calculating VCI a control response may be made to increase or decrease in filling pressure.

Individual press specifications, such as proportional valve design, servo motor power output, barrel diameter, hydraulic capacity, check ring performance, and other press variables may be accounted for in the calculation of the control variables by using ratios or by using dimensionless factors.

The flowability of a polymer material may vary during an injection molding process for several reasons. A nominal viscosity of the polymer may vary slightly from batch-to-batch due to inconsistent manufacturing or poor quality control. When running a molding operation, these viscosity variations result in a change in the pressures required to fill the mold cavity. These viscosity variations can result in quality issues, and reduced productivity. For example, if the viscosity increases substantially, the injection molding system may not produce adequate force to push the polymer into the mold, thus resulting in a "short shot". Furthermore, parts can become trapped in the mold if the short shot region prevents the part from being properly ejected from the mold, and the trapped part can damage the mold upon closing of the mold in preparation for the next shot of polymer. This is especially concerning in the case of a soft metallurgy mold, such as aluminum, where the material is more easily deformed than harder materials, such as hardened tools steels. If the polymer viscosity decreases substantially, too much pressure may be applied to fill the mold resulting in "flashing" the mold. When flashing occurs a parting line edge can become damaged as material is forced between shut off surfaces. Flashing is especially concerning in the case of a soft metallurgy mold, such as aluminum, where the material is more easily deformed than harder materials, such as hardened tools steels.

In the case of recycled polymers, the feedstock is highly variable due to the multiple sources of material that are blended together to form a batch of recycled resin. The recycler seeks to blend many different melt flow index (MFI) resins together to achieve a target average MFI. However, the materials comprising the blend are highly variable, and thus the resulting blend can range as much as plus or minus 10 MFI, or even greater. For the processor, this creates a difficult processing scenario, since the MFI variation causes constant changes in processing conditions. In this case, the machine operator must regularly monitor the process and resulting parts and make regular corrections to the process to avoid producing scrap parts or damaging the mold.

The addition of colorant masterbatch may also result in a change in the viscosity of the polymer. These viscosity variations require the molding machine operator to make processing adjustments to account for these variations. Furthermore, the masterbatch is concentrated and added at a relatively low levels typically ranging from about 0.5 to about 10% of the total material composition. Small variations in the addition of the masterbatch, which is inherent in the metering methods of masterbatch addition, can result in large swings in polymer viscosity. As a result, the operator must tend to the molding machine to make needed adjustments to avoid producing scrap parts or damaging the mold.

Viscosity is also temperature dependent. In a molding operation, the temperature of the water cooling a molding system may vary. For example, when using tower water to cool a mold the temperature of the water will be higher on a warmer day, especially after continued warm weather, and will be cooler in the evening or during prolonged cooler weather. These temperature variations may cause the viscosity of the material in the molding system to change. As a result, part quality varies and creates the potential for scrap and damage to the mold. Other sources of temperature variation may include temperature variations that occur in the nozzle, or in the heater bands maintaining an elevated temperature in the feed system. Molding equipment operators must continually monitor and adjust for these temperature swings.

In order to correct the problems caused by changes in flowability, the controller **50** (FIG. **1**) may cause the screw control **26** (FIG. **1**) to increase or decrease movement of the reciprocating screw **22** based on the change in flowability to maintain a target injection pressure.

Turning now to FIG. **10**, the logic diagram **1400** of the process for accounting for changes in viscosity is illustrated. An injection molding machine with at least one mold cavity is provided at **1410**. an injection molding controller is provided at **1420**, which includes a pressure control output that is configured to provide a control signal, which, at least partially, determines an injection molding pressure for the injection molding process of the injection molding machine. A first control signal is measured at **1430** at a first time in the injection molding cycle. A second control signal is measured at **1440** at a second time in the injection molding cycle, subsequent to the first time. The first control signal from the pressure control output and the second control signal from the pressure control output are compared at **1450**. A third control signal for the pressure control output is determined at **1460** at a third time, subsequent to the second time, the third control signal being based at least in part on the comparison result.

FIG. **11** illustrates one embodiment of a closed loop control system that may be used to carry out the method illustrated in FIG. **10**. The control system **1700** illustrated in FIG. **11** provides an open architecture for those skilled in the art to implement and refine the injection molding process illustrated in FIG. **10** for particular parts or materials by using any one or more the process variables represented generally by reference numeral **1710**. These process variables **1710** represent physical values obtained from various sensors in the injection molding machine. These physical values are processed by the controller **50**. The processing may include any number of calculations such as the calculations indicated by reference numeral **1712**. These calculations may be used for conversion or scaling in order to reflect the importance of particular variables through weighting. Such calculations may incorporate rule based algorithms, heuristic algorithms, genetic algorithms, or other calculations, such as the calculations described above with respect flow factor and viscosity change index.

The process variables **1710** may be used directly, with or without scaling, or via variable calculations **1712**, to just a core variable **1714**, and to determine a control variable **1716**, such as a control signal. For example, the variable calculations **1712** may include the VCI or flow factor calculations **1713** described above. The control variable **1716** represents a feedback signal for the PID control loop **1718**. While any number of desired setpoints, generally represented by reference numeral **1720**, may be used as an input to the PID control loop **1718**, the systems and methods described herein, which are pressure control injection molding processes, generally use changes in injection pressure **1722** as a control input. As a result, the PID control loop **1718** continuously adjusts a control signal that is sent to the proportional valve **1724**, thereby continuously accounting for changes in the flowability of the molten plastic material.

In some cases, the injection molding machine may include an electric press and the controller may vary an electronic control signal to a servo motor of the electric press.

As discussed above, changes in the viscosity of the molten plastic material may be caused by any number of factors. For example, an operator may desire to reuse poor quality parts by re-grinding the poor quality parts and mixing the reground plastic material with virgin plastic material. Mixing of regrind and virgin plastic material will change the MFI of the combined material. Similarly, an operator may desire to change part color during an injection run by introducing a colorant into the molten plastic material. The introduction of a colorant will often change the MFI of the molten plastic material. Finally, changes in ambient operating conditions can also change the viscosity of the molten plastic material. For example, if ambient temperature increases, viscosity of the molten plastic material often increases. Likewise, if ambient temperature decreases, viscosity the molten plastic material often decreases.

The disclosed low constant pressure injection molding methods and machines advantageously reduce cycle time for the molding process while increasing part quality. Moreover, the disclosed low constant pressure injection molding machines may employ, in some embodiments, electric presses, which are generally more energy efficient and require less maintenance than hydraulic presses. Additionally, the disclosed low constant pressure injection molding machines are capable of employing more flexible support structures and more adaptable delivery structures, such as wider platen widths, increased tie bar spacing, elimination of tie bars, lighter weight construction to facilitate faster movements, and non-naturally balanced feed systems. Thus, the disclosed low constant pressure injection molding machines may be modified to fit delivery needs and are more easily customizable for particular molded parts.

Additionally, the disclosed low constant pressure injection molding machines and methods allow the molds to be made from softer materials (e.g., materials having a Rc of less than about 30), which may have higher thermal conductivities (e.g., thermal conductivities greater than about 20 BTU/HR FT ° F.), which leads to molds with improved cooling capabilities and more uniform cooling. Because of the improved cooling capabilities, the disclosed low constant pressure injection molds may include simplified cooling systems. Generally speaking, the simplified cooling systems include fewer cooling channels and the cooling channels that are included may be straighter, having fewer machining axes. One example of an injection mold having a simplified cooling system is disclosed in U.S. Patent Application No. 61/602,781, filed Feb. 24, 2012, which is hereby incorporated by reference herein.

The lower injection pressures of the low constant pressure injection molding machines allow molds made of these softer materials to extract 1 million or more molding cycles, which would not be possible in conventional injection molding machines as these materials would fail before 1 million molding cycles in a high pressure injection molding machine.

It is noted that the terms "substantially," "about," and "approximately," unless otherwise specified, may be utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. These terms are also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue. Unless otherwise defined herein, the terms "substantially," "about," and "approximately" mean the quantitative comparison, value, measurement, or other representation may fall within 20% of the stated reference.

It should now be apparent that the various embodiments of the products illustrated and described herein may be produced by a low, substantially constant pressure molding process. While particular reference has been made herein to products for containing consumer goods or consumer goods products themselves, it should be apparent that the molding method discussed herein may be suitable for use in conjunction with products for use in the consumer goods industry, the food service industry, the transportation industry, the medical industry, the toy industry, and the like. Moreover, one skilled in the art will recognize the teachings disclosed herein may be used in the construction of stack molds, multiple material molds including rotational and core back molds, in combination with in-mold decoration, insert molding, in mold assembly, and the like.

Part, parts, or all of any of the embodiments disclosed herein can be combined with part, parts, or all of other injection molding embodiments known in the art, including those described below.

Embodiments of the present disclosure can be used with embodiments for injection molding at low constant pressure, as disclosed in U.S. patent application Ser. No. 13/476,045 filed May 21, 2012, entitled "Apparatus and Method for Injection Molding at Low Constant Pressure" (applicant's case 12127) and published as US 2012-0294963 A1, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for pressure control, as disclosed in U.S. patent application Ser. No. 13/476,047 filed May 21, 2012, entitled "Alternative Pressure Control for a Low Constant Pressure Injection Molding Apparatus" (applicant's case 12128) now U.S. Pat. No. 8,757,999, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for non-naturally balanced feed systems, as disclosed in U.S. patent application Ser. No. 13/476,073 filed May 21, 2012, entitled "Non-Naturally Balanced Feed System for an Injection Molding Apparatus" (applicant's case 12130) and published as US 2012-0292823 A1, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for injection molding at low, substantially constant pressure, as disclosed in U.S. patent application Ser. No. 13/476,197 filed May 21, 2012, entitled "Method for Injection Molding at Low, Substantially Constant Pressure" (applicant's case 12131Q) and published as US 2012-0295050 A1, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for injection molding at low, substantially constant pressure, as disclosed in U.S. patent application Ser. No. 13/476,178 filed May 21, 2012, entitled "Method for Injection Molding at Low, Substantially Constant Pressure" (applicant's case 12132Q) and published as US 2012-0295049 A1, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for co-injection processes, as disclosed in U.S. patent application Ser. No. 13/774,692 filed Feb. 22, 2013, entitled "High Thermal Conductivity Co-Injection Molding System" (applicant's case 12361), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding with simplified cooling systems, as disclosed in U.S. patent application Ser. No. 13/765,428 filed Feb. 12, 2013, entitled "Injection Mold Having a Simplified Evaporative Cooling System or a Simplified Cooling System with Exotic Cooling Fluids" (applicant's case 12453M), now U.S. Pat. No. 8,591,219, which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding thinwall parts, as disclosed in U.S. patent application Ser. No. 13/476,584 filed May 21, 2012, entitled "Method and Apparatus for Substantially Constant Pressure Injection Molding of Thinwall Parts" (applicant's case 12487), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding with a failsafe mechanism, as disclosed in U.S. patent application Ser. No. 13/672,246 filed Nov. 8, 2012, entitled "Injection Mold With Fail Safe Pressure Mechanism" (applicant's case 12657), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for high-productivity molding, as disclosed in U.S. patent application Ser. No. 13/682,456 filed Nov. 20, 2012, entitled "Method for Operating a High Productivity Injection Molding Machine" (applicant's case 12673R), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding certain thermoplastics, as disclosed in U.S. patent application Ser. No. 14/085,515 filed Nov. 20, 2013, entitled "Methods of Molding Compositions of Thermoplastic Polymer and Hydrogenated Castor Oil" (applicant's case 12674M), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for runner systems, as disclosed in U.S. patent application Ser. No. 14/085,515 filed Nov. 21, 2013, entitled "Reduced Size Runner for an Injection Mold System" (applicant's case 12677M), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for moving molding systems, as disclosed in U.S. patent application 61/822,661 filed May 13, 2013, entitled "Low Constant Pressure Injection Molding System with Variable Position Molding Cavities:" (applicant's case 12896P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for injection mold control systems, as disclosed in U.S. patent application 61/861,298 filed Aug. 20, 2013, entitled "Injection Molding Machines and Methods for Accounting for Changes in Material Properties During Injection Molding Runs" (applicant's case 13020P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for injection mold control systems, as disclosed in U.S. patent application 61/861,304 filed Aug. 20, 2013, entitled "Injection Molding Machines and Methods for Accounting for Changes in Material Properties During Injection Molding Runs" (applicant's case 13021P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for injection mold control systems, as disclosed in U.S. patent application 61/861,310 filed Aug. 20, 2013, entitled "Injection Molding Machines and Methods for Accounting for Changes in Material Properties During Injection Molding Runs" (applicant's case 13022P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for using injection molding to form overmolded articles, as disclosed in U.S. patent application 61/918,438 filed Dec. 19, 2013, entitled "Methods of Forming Overmolded Articles" (applicant's case 13190P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for controlling molding processes, as disclosed in U.S. Pat. No. 5,728,329 issued Mar. 17, 1998, entitled "Method and Apparatus for Injecting a Molten Material into a Mold Cavity" (applicant's case 12467CC), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for controlling molding processes, as disclosed in U.S. Pat. No. 5,716,561 issued Feb. 10, 1998, entitled "Injection Control System" (applicant's case 12467CR), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding preforms, as disclosed in U.S. patent application 61/952,281, entitled "Plastic Article Forming Apparatus and Methods for Using the Same" (applicant's case 13242P), which is hereby incorporated by reference.

Embodiments of the present disclosure can be used with embodiments for molding preforms, as disclosed in U.S. patent application 61/952,283, entitled "Plastic Article Forming Apparatus and Methods for Using the Same" (applicant's case 13243P), which is hereby incorporated by reference. The dimensions and values disclosed herein are not to be understood as being strictly limited to the exact numerical values recited. Instead, unless otherwise specified, each such dimension is intended to mean both the recited value and a functionally equivalent range surrounding that value. For example, a dimension disclosed as "40 mm" is intended to mean "about 40 mm."

Every document cited herein, including any cross referenced or related patent or application and any patent application or patent to which this application claims priority or benefit thereof, is hereby incorporated herein by reference in its entirety unless expressly excluded or otherwise limited. The citation of any document is not an admission that it is prior art with respect to any invention disclosed or claimed herein or that it alone, or in any combination with any other reference or references, teaches, suggests or discloses any such invention. Further, to the extent that any meaning or definition of a term in this document conflicts with any meaning or definition of the same term in a document incorporated by reference, the meaning or definition assigned to that term in this document shall govern.

While particular embodiments of the present invention have been illustrated and described, it would be obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the invention. It is therefore intended to cover in the appended claims all such changes and modifications that are within the scope of this invention.

What is claimed is:

1. A method of automatically adjusting an injection molding process to compensate for variations in the flowability of a molten plastic material, the method comprising:

providing an injection molding machine with at least one mold cavity;

providing an injection molding controller, which includes a pressure control output that is configured to generate a control signal, which, at least partially determines an injection molding pressure for the injection molding process of the injection molding machine;

measuring a first control signal generated from the pressure control output at a first time in an injection molding cycle;

measuring a second control signal generated from the pressure control output at a second time in the same injection molding cycle, subsequent to the first time;

comparing the first control signal generated from the pressure control output and the second control signal generated from the pressure control output to obtain a comparison result; and

determining a third control signal for the pressure control output, based at least in part on the comparison result, at a third time that is subsequent to the second time.

2. The method of claim **1**, wherein the determining includes determining the third control signal at a third time, which is within the same injection molding cycle as the second time.

3. The method of claim **1**, wherein the third time is located in a subsequent molding cycle from the second time.

4. The method of claim **1**, including:

determining a time difference between the first time and the second time; and

wherein the comparing includes comparing the first control signal and the second control signal, based, at least in part, on the time difference, to obtain the comparison result.

5. The method of claim **4**, wherein the comparison result is a flow factor (FF) that is used as a soft sensor melt viscosity input to by the controller.

6. The method of claim 5, wherein the FF is determined by the formula:

$$FF=(CS1-CS2)/T;$$

where CS1 is the first control signal;
CS2 is the second control signal; and
T is the time difference between CS1 and CS2.

7. The method of claim 6, wherein the third control signal is proportional to the flow factor.

8. The method of claim 6, wherein T is between 0.1 milliseconds and 10 milliseconds.

9. The method of claim 6, wherein T is about 1 millisecond.

10. The method of claim 1, wherein the comparison result is used as a basis for a viscosity change index (VCI) that is used as a soft sensor melt viscosity input to by the controller.

11. The method of claim 10, wherein the VCI is determined by the following formula:

$$VCI=(CS1-CS2)/S$$

where CS1 is a first control signal;
CS2 is a second control signal; and
S is the position difference for the a melt moving machine component.

12. The method of claim 11, wherein the third control signal is proportional to the VCI.

13. The method of claim 11, wherein S is between 0.5 microns and 10 microns.

14. The method of claim 11, wherein S is about 1 micron.

15. The method of claim 11, wherein the first control signal and the second control signal are measured before the molten plastic material fills more than 90% of a mold cavity.

16. The method of claim 1, wherein the comparing of the first control signal and the second control signal includes comparing the first control signal and the second control signal to optimal control signals based on an optimal pressure curve.

17. The method of claim 1, wherein the providing of the injection molding machine includes providing a melt moving machine component; and further comprising:

measuring a first position of the melt moving machine component at the first time;

measuring a second position of the melt moving machine component at the second time;

determining a position difference between the first position and the second position; and

wherein the comparing includes comparing the first control signal and the second control signal, based, at least in part, on the position difference, to obtain the comparison result.

18. The method of claim 1, further comprising controlling the injection molding pressure by sending the third control signal to a melt pressure control device.

19. A controller configured to automatically adjust an injection molding process to compensate for variations in the flowability of a molten plastic material, the controller adapted to:

measure a first control signal generated from a pressure control output of the controller at a first time in an injection molding cycle using a control signal measurement device;

measure a second control signal generated from the pressure control output of the controller at a second time in the same injection molding cycle, subsequent to the first time using the control signal measurement device;

compare the first control signal generated from the pressure control output of the controller and the second control signal generated from the pressure control output of the controller to obtain a comparison result; and

determine a third control signal for the pressure control output, based at least in part on the comparison result, at a third time that is subsequent to the second time.

20. The controller of claim 19, wherein the controller is adapted to be used with an injection molding machine.

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